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Granular Activated Carbon Adsorption and Fluid-Bed Reactivation at Manchester, New Hampshire

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Municipal Environmental Research Lab.
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GRANULAR ACTIVATED CARBON ADSORPTION AND FLUID-BED REACTIVATION
AT
MANCHESTER, NEW HAMPSHIRE

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Cooperative Agreement No. CR805371

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16. ABSTRACT

Treatment performances of virgin and reactivated GAC were evaluated during three reactivation-exhaustion cycles by measuring total organic carbon (TOC), trihalomethanes (THM), and trihalomethane formation potential (THMFP). GAC adsorptive capacity was measured using traditional test parameters including iodine number, molasses decolorizing index, BET, and pore-size distribution. The GAC was reactivated on-site by a 500 lb/hr fluidized-bed unit.

Results of this study demonstrated that onsite reactivation was a cost-effective method of restoring the adsorptive properties of spent GAC. During a 10-month period, more than 1.8 million lb of GAC was reactivated at a total cost of less than 22¢/lb as compared with a delivered cost of 61.5¢/lb for virgin GAC. The average total carbon loss resulting from transportation and reactivation was 11.5% by volume.

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UNITED STATES DEPARTMENT OF COMMERCE
The Assistant Secretary for Administration
Washington, D.C. 20230

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MEMORANDUM FOR ALL EMPLOYEES
Office of the Secretary
United States Travel and Tourism Administration
Office of the Under Secretary for Economic Affairs
Assistant Secretary for Productivity, Technology and Innovation
Office of the Chief Economist
Bureau of Economic Analysis
Bureau of Industrial Economics
National Technical Information Service
National Telecommunications and Information Administration (excluding ITS Boulder)
Minority Business Development Agency - Headquarters and Washington, D.C. Regional Office

Jo Ann Sondey-Hersh

FROM: Jo Ann Sondey-Hersh
Personnel Officer

SUBJECT: Absence for Voting

The November 8th elections are drawing near. For your convenience, the following summarizes the Department's excused absence for voting policy:

- Generally, where polls are not open at least three hours before or after an employee's regular work hours, the employee may be granted excused absence. Employees may be permitted to report for work three hours after the polls open or, may leave work three hours before the polls close, whichever requires less excused time. Excused absences for employees on flexible work schedules are determined by the former fixed hours of the unit.

- Where these general rules do not permit sufficient time to vote, additional excused time not to exceed eight hours may be granted. For example, if an employee's voting place is beyond normal commuting distance and vote by absentee ballot is not permitted, sufficient time for travel may be granted. Time in excess of eight hours shall be charged to annual leave, or if annual leave is exhausted, to leave without pay.

In the Washington metropolitan area, polls are open as follows:

District of Columbia - 7:00 AM - 8:00 PM
Virginia - 6:00 AM - 7:00 PM

Questions concerning excused absence for voting should be directed to your servicing Personnel Specialist.

UNITED STATES DEPARTMENT OF COMMERCE
The Assistant Secretary for Administration
Washington, D.C. 20230

OCT 27 1983

MEMORANDUM FOR All Commerce Employees

From: John M. Golden
Director of Personnel

Subject: Health Benefits Open Season, November 14 - December 9, 1983

An open season, during which eligible Federal employees may enroll or change enrollment to a new Federal Employees Health Benefits (FEHB) Plan, will be held from November 14 - December 9, 1983.

Distribution of open season literature will be made through administrative officers prior to November 14. This year, each employee should receive the following material:

- o 1984 Enrollment Information Guide and Plan Comparison Chart (BRI 41-331):

  This booklet contains open season enrollment information for Federal civilian employees. It also contains general information about the Federal Employees Health Benefits Program and plans, charts comparing the benefits of all plans, and bi-weekly and monthly rates for each plan for 1984.

- o Addenda to the brochures for each plan:

  The addenda will set forth any changes to each plan's benefits, which will be effective beginning January 1, 1984.

  If, after examining the comparison chart included in BRI 41-331, you decide that you are interested in enrolling in, or changing to, a particular plan, consult the brochure of the plan for a complete description of benefits. Brochures will be available for your inspection at your personnel office.

DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement number CR805371 to the Manchester Water Works. It has been subject to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names for commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater, solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communication link between the researcher and the user community.

This report presents the results of a drinking water research effort to evaluate the cost and performance of a granular activated carbon reactivation system using a full-scale, 226.8 kg/hr (500 lbs/hr) fluidized bed furnace and a semiautomatic carbon transport mechanism located at the Manchester Water Treatment facility in Manchester, New Hampshire. The production and removal of trihalomethanes and the effectiveness of reactivated granular carbon at this facility are compared over several reactivation cycles.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

This study was designed to evaluate the actual cost and performance of a fluidized-bed granular activated carbon (GAC) reactivation system, a semiautomatic GAC transport system, and a GAC water treatment system at the Manchester Water Works, Manchester, New Hampshire.

GAC performance was monitored in one of the utility's four 3.80×10^4 m^3/day (10 mgd) filters to obtain a side by side comparison of virgin carbon and reactivated 5-year-old service carbon performance over three complete reactivation cycles. The filter was divided at its midpoint and then operated and monitored until a steady-state condition was achieved in each filter half for TOC and THM removal about 90 days into each cycle. For a portion of the study, GAC filter media was educted through a semiautomatic transport system retrofitted to the existing filters. Operation of this semiautomatic system proved to be unreliable however and was subsequently abandoned and replaced by a hand held eductor system. GAC from the utility's three remaining filters was also reactivated to obtain additional performance data and to restore the adsorptive capacity of the spent service carbon.

Treatment performance of the virgin and reactivated GAC was evaluated by measuring TOC, THM, and THMFP values during each cycle. GAC adsorptive capacity was measured using traditional test parameters including iodine number, molasses decolorizing index, BET and pore-size distribution analyses. Fluid-bed reactivation effectively restored GAC adsorptive properties to essentially a virgin state.

With the cooperation of three regional water utilities, a short-term program of regional reactivation was also investigated. The actual costs and feasibility of transporting and reactivating GAC from these utilities were determined.

This report was submitted in fulfillment of Cooperative Agreement No. CR805371 by the Manchester Water Works under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period March 1977 to April 1982, and work was completed as of November 30, 1982.

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ABBREVIATIONS AND SYMBOLS

AC	Apparent Color of Aqueous Samples
AD	Apparent Density
ADF	Average Daily Flow
AMB	Ambient Temperature
AN	Abrasion Number
BET	Surface Area
C	Centigrade
^{o}C	Degrees Centigrade
cc	Cubic Centimeters
CCT	Total Combined GAC Filter Operating Hours (Hours/Day)
Ce	GAC Effluent Concentration
CFU	Colony Forming Unit
$CHBrCl_2$	Bromodichloromethane
$CHBr_2Cl$	Dibromochloromethane
$CHBr_3$	Bromoform
$CHCL_3$	Chloroform
Ci	GAC Influent Concentration
cm	Centimeters
CO_2	Carbon Dioxide
CTS	Carbon Transport System
DI	Decolorizing Index
DIU	Decolorizing Index Units
DPD	N, N-Diethyl-P-Phenylenediamine Method for Chlorine Residual Measurement
DS	Dewatering Screw
EBCT	Empty Bed Contact Time
ECD	Electron Capture Detector
ED	Eductor
E.M.S.L.	U.S. Environmental Monitoring Support Laboratory
EPA	United States Environmental Protection Agency
ERT	Environmental Research and Technology Co.
^{o}F	Degrees Fahrenheit
FBR	Fluid-Bed Reactivator
Ft	Feet
Ft^2	Square Foot
GAC	Granular Activated Carbon
GC	Gas Chromatograph
gm	Grams
GPM	Gallons Per Minute
gpm/ft^2	Gallons Per Minute Per Square Foot
H^2	Hydrogen
H_3PO_4	Concentrated (85%) Phosphoric Acid - Reagent Grade

hrs	-	Hours
in	-	Inch
IN	-	Iodine Number
ITHM	-	Instantaneous Trihalomethanes
K_2PtCl_6	-	Potassium Chloroplatinate
$K_2S_2O_8$	-	Potassium Persulfate - Reagent Grade
Kg	-	Kilograms
$KH(IO_3)_2$	-	Potassium Biniodate
KHP_2	-	Potassium Hydrogen Phthalate - Reagent Grade
km^2	-	Square Kilometers
KPa	-	Kilo Pascal
KWH	-	Kilowatt Hour
L	-	Liter
340L	-	Low Carbon Stainless Steel
Lbs	-	Pounds
m	-	meter
m^3	-	Cubic Meters
m^3/day	-	Cubic Meters Per Day
mg	-	Milligrams
MGD	-	Million Gallons Per Day
MGLD	-	Megaliter Per Day
Min	-	Minutes
mL	-	Milliliter
mm	-	Millimeter
MPD	-	Mean Particle Diameter
MPV	-	Modified Phenol Value
MWW	-	Manchester Water Works
N/A	-	Not Applicable
Na_2CO_3	-	Sodium Carbonate - Reagent Grade
NPOC	-	Nonpurgeable Organic Carbon
NTU	-	Nephlometric Turbidity Unit
%A	-	Percent Ash
%V	-	Percent Volatiles
pH	-	Hydrogen Ion Concentration
POC	-	Purgeable Organic Carbon
PSD	-	Pore Size Distribution
psi	-	Pounds Per Square Inch
Q	-	WTP Daily Productions (MGLD)
QC	-	Quality Control
QT	-	Quench Tank
rpm	-	Revolutions Per Minute
RV	-	Rotary Valve
SA	-	Sieve Analysis
SC	-	Service Carbon
SPC	-	Standard Plate Count
SR	-	Tray Scrubber
ST-1	-	Spent GAC Storage Tank
ST-2	-	Reactivated GAC Storage Tank
TC	-	Total Coliform
TFT	-	Test Filter Operating Hours (Hours/Day)
THM	-	Trihalomethane
THMFP	-	Trihalomethane Formation Potential

TOC - Total Organic Carbon
ug - Micrograms
uL - Microliters
VC - Virgin Carbon
VM - Volatile Matter
VOA - Volatile Organic Analysis
W.D. - Water Depth
wk - Week
WTP - Manchester, NH Water Treatment Plant

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Special appreciation is also extended to Katharine Lane for her valuable assistance in the Manchester Water Works laboratory and to Sandra Skalkeas for her assistance in the preparation of this report.

Valuable assistance was also provided by the Massachusetts Department of Environmental Quality Engineering, and the water departments of Danvers, Massachusetts, Lowell, Massachusetts and the Connecticut Water Company in conjunction with the regional reactivation phase of this project.

This research project was a cooperative effort with technical assistance provided by Ben Lykins and Jack DeMarco of the U.S. Environmental Protection Agency.

SECTION 1

INTRODUCTION

In keeping with the research goals of the Safe Drinking Water Act (Public Law 93-523), the U.S. Environmental Protection Agency (USEPA) and the Manchester Water Works (MWW) entered into a cooperative agreement to evaluate the cost and performance of a fluidized-bed, GAC reactivation system plus related facilities at the Manchester Water Treatment Plant. This study included funding to explore the efficiency of GAC before and after reactivation and a limited evaluation of GAC reactivation for other water utilities in the New England region.

As early as 1975, Manchester Water Works officials began evaluating alternatives available for reactivation or replacement of approximately 453,592 kg (500 tons) of GAC used at the City's 151,000 m^3/day (40-MGD) water treatment plant. The investigation revealed that on-site reactivation was the most cost-effective method of restoring the adsorptive properties of the GAC for the conditions at Manchester.

Because the research project spanned a period of nearly 5 years (July 1977 to April 1982), the project work was subdivided into 3 major investigative phases. Specific objectives which were established for each phase of the project included:

Phase I

- To design, construct, and operate a GAC fluid-bed reactivation system and semiautomatic carbon transport system.
- To establish analytical capabilities at the treatment facility to monitor GAC performance.

Phase II

- To determine the cost and performance of a full-scale, on-site fluid-bed GAC reactivation system.
- To determine the cost and performance of a semiautomatic carbon transport system.

- To evaluate the adsorptive performance of GAC before and after reactivation over several reactivation cycles using virgin GAC as a control.

- To estimate carbon losses resulting from the reactivation and transport of GAC.

Phase III

- To determine the cost and performance of reactivating GAC for other water utilities in the New England region on a limited basis.

SECTION 2

CONCLUSIONS

The investigation of a full-scale fluid-bed reactivation and GAC treatment system at Manchester, New Hampshire has supplied the waterworks industry with significant information. The project demonstrated that onsite GAC reactivation at a medium-sized water treatment facility is feasible, practical, and cost effective. A fluid-bed reactivation furnace was shown to be a practical addition to a water treatment process scheme provided a capable work force could be properly trained to operate and maintain the equipment. During a 10-month period from June 1980 to March 1981, the MWW reactivated more than 1.8 million pounds of GAC at a total cost of 21.7¢ per pound in comparison to a delivered cost to Manchester of 61.5¢ per pound for virgin GAC.

The analytical research undertaken at Manchester showed that without exception, fluidized-bed reactivation of spent GAC is a cost-effective means of restoring its overall adsorptive capacity. The adsorptive performance of GAC reactivated once, twice, or three times equaled and, in most cases, surpassed the adsorptive performance of virgin carbon. The experimental research scheme made it possible to minimize most treatment variables affecting GAC adsorptive performance measurements. It was demonstrated that as carbon is reactivated repeatedly, adsorptive capacity is completely restored after each reactivacation cycle.

GAC losses were determined to be the largest single cost item in the economic evaluation of onsite carbon reactivation at the MWW. Consequently, accurate measurement of such losses received considerable attention during the research program. Data gathered at controlled test sites revealed that the average total carbon loss for transportation and reactivation of the GAC over 5-reactivation cycles was 11.5% by volume. Carbon losses resulting from reactivation were considerably greater than the amount reported in the manufacturer's literature.

Other areas of investigation concerned the physical processes of the fluid-bed reactivation facility. Off-gas samples were collected to determine compliance with State of New Hampshire air emission standards and to serve other investigative purposes. Results demonstrated that the fluid-bed unit was discharging less than 0.045 kg per hour (0.1 pound per hour) of particulate matter to the atmosphere, compared with an allowable state standard of 0.779 kg per hour (1.73 pounds per hour). A stack analysis for volatile organics (VOA) was also performed revealing that only chloroform was present in the off-gas.

The research project had 2 distinct periods of operation: The first 14 months, which involved frequent startup problems, and the following 10 months, which were characterized by a very successful reactivation operation. The major problem of the first period was a lack of equipment efficiency due to a high frequency of mechanical and electrical difficulties. The operating factor of the reactivation furnace was approximately 30% through this initial 14 month period of operation. Use of the carbon transport equipment was eventually abandoned because of incompatibility with existing filter equipment, faulty new equipment, excessive maintenance, and unacceptable percent removal of the filter media. A manually-operated hose and eductor system was substituted and used successfully to transport the GAC.

An expenditure of roughly $100,000 was required to modify the reactivator equipment for successful operation. The operating factor of equipment was improved to a level of about 75% as a result. The corrective actions that were implemented by the MWW resulted in smooth and reliable operation of the GAC reactivation facility. Combined factors of equipment reliability, GAC adsorptive performance, and reactivation cost have demonstrated the advantages of onsite GAC reactivation at this location.

The overall success of research work at the MWW lead to an investigation of using the Manchester facility as a regional reactivation center. Approximately 18,144 kg (40,000 pounds) of GAC was reactivated at each of the 3 separate water utilities. The results of this research effort demonstrated that it was economically feasible for MWW to provide a GAC reactivation service for other water utilities in the New England region.

SECTION 3

RECOMMENDATIONS

1. Automated equipment for transporting GAC must be improved since effective and reliable automated GAC transport equipment is not currently available on the market.

2. Fluid-bed reactivation equipment should be improved. Work needs to be done to reduce equipment down time to minimize GAC losses, and to increase equipment longevity.

3. Noncorrosive materials need to be identified for use in transporting and reactivating GAC.

4. Evaluation of the mechanism used for storing, retrieving, assembling and interpreting data is needed.

5. Further research is needed to examine the characteristics of both the gaseous and liquid effluents from the reactivator to determine their environmental influence.

6. The specific location of low molecular weight volatile organic carbon desorption in the fluid bed system should be determined to understand fully the dynamics of the fluidized-bed system.

7. The nature of inorganic adsorption-reactivation mechanisms should be explored. The interference or enhancement of organic adsorption in reactivated GAC systems with competitive inorganic adsorbate constituents is not presently known.

8. The effect of 4 or more reactivations on GAC for organic and inorganic adsorption as well as for practical filter operation should be studied in view of lower values in apparent density and mean particle diameter observed through each reactivation cycle.

9. Studies should be made to determine the effect of fluidized-bed reactivation on other grades and types of GAC.

10. A simple and rapid test method should be developed to facilitate quality control over fluid-bed reactivation operations.

11. A plant-scale study should be conducted on the effects of competitive adsorption on reactivated GAC and the influence of changing pore size distribution as a result of repeated reactivation.

12. Identification of small quantities of sand in GAC from regional GAC utilities should be studied and a cost-effective means for separating sand from the GAC should be developed.

SECTION 4

TREATMENT PLANT DESIGN AND OPERATION

General

Manchester is a diversified industrial-residential city in the southern part of New Hampshire, approximately 89 kilometers (55 miles) north of Boston. The MWW supplies approximately 105,000 consumers in the City of Manchester and 5 surrounding towns with an average daily flow of 4.94×10^4 m^3/day (13 MGD). Water service is provided through 166.6×10^3 m^3 (44 million gallons) of covered reservoir storage and approximately 604 kilometers (375 miles) of distribution main, ranging in size from 15.2 cm to 121.9 cm (6 inch to 48 inch) pipe. Lake Massabesic, the sole source of supply, is situated within a 103.6 km^2 (40 square mile) area consisting mostly of sparsely developed forest land. The quality of the lake supply can be generally described as very good in comparison to other New England surface waters with exception of a moderately high color value (averaging about 25 units) and occasional problems with taste and odor due to algae. Humic acids, which may contribute to the organic color, are the result of extensive forest vegetation and watershed lowland.

Water Treatment Plant

The Manchester Water Treatment Plant is located on the outskirts of Manchester, adjacent to Lake Massabesic (see Figure 1). The plant facility (Table 1) was constructed in 1974 and has a maximum delivery capacity of 1.52×10^5 m^3/day (40 MGD). Treatment consists of flash mixing, followed by flocculation, sedimentation, and series filtration through individual beds of sand and GAC filter media. Pretreatment chemicals include 50% aluminum sulfate applied at an average dosage of 16 mg/L and 50% sodium aluminate applied at an average dosage of 10 mg/L. Each of the rapid sand filters has 27.9 cm (11 inches) of bed depth with an effective size of 0.55 to 0.65 mm and uniformity coefficient of 1.5. The 4 GAC filters each contain a 122 cm (48 inch) deep bed of 8 x 30 mesh coal base carbon. All of the plant filters are equipped with automatic backwash (ABW) filter carriages which travel the length of a filter individually backwashing the compartmented filter cells thereby permitting a filter to remain in service during the backwash cycle.

Treated water at Manchester is both pre and post chlorinated with prechlorine being added just before the sand filters at an average dosage of 1 mg/L. Post chlorination dosages are applied in the 1.0 to 2.0 mg/L range resulting in concentrations in the distribution system ranging from trace amounts to about 0.7 mg/L. In addition to chlorine, the finished water is also treated with about 3 mg/L of 25% sodium hydroxide raising the pH to about 7.2 and about 1 mg/L of bi-metallic glossy phosphate to control corrosion in the distribution system. Table 2 presents a summary of typical water quality data at the MWW.

The treatment plant is equipped with a complete water testing laboratory which is staffed by a plant manager/chemist, and laboratory technician. Operational staffing consists of 10 full-time plant operators. All personnel report to a civil engineer who is also the person in charge of the utility's water supply division operations. The operators operate and maintain all of the plant equipment including the carbon reactivation system, gas turbine generators, sodium hypochlorite generator and several remote pumping stations including a 375 KW hydrogenerator. The water treatment facility is manned on a full-time basis with a minimum of 2 operators per shift, 7 days a week.

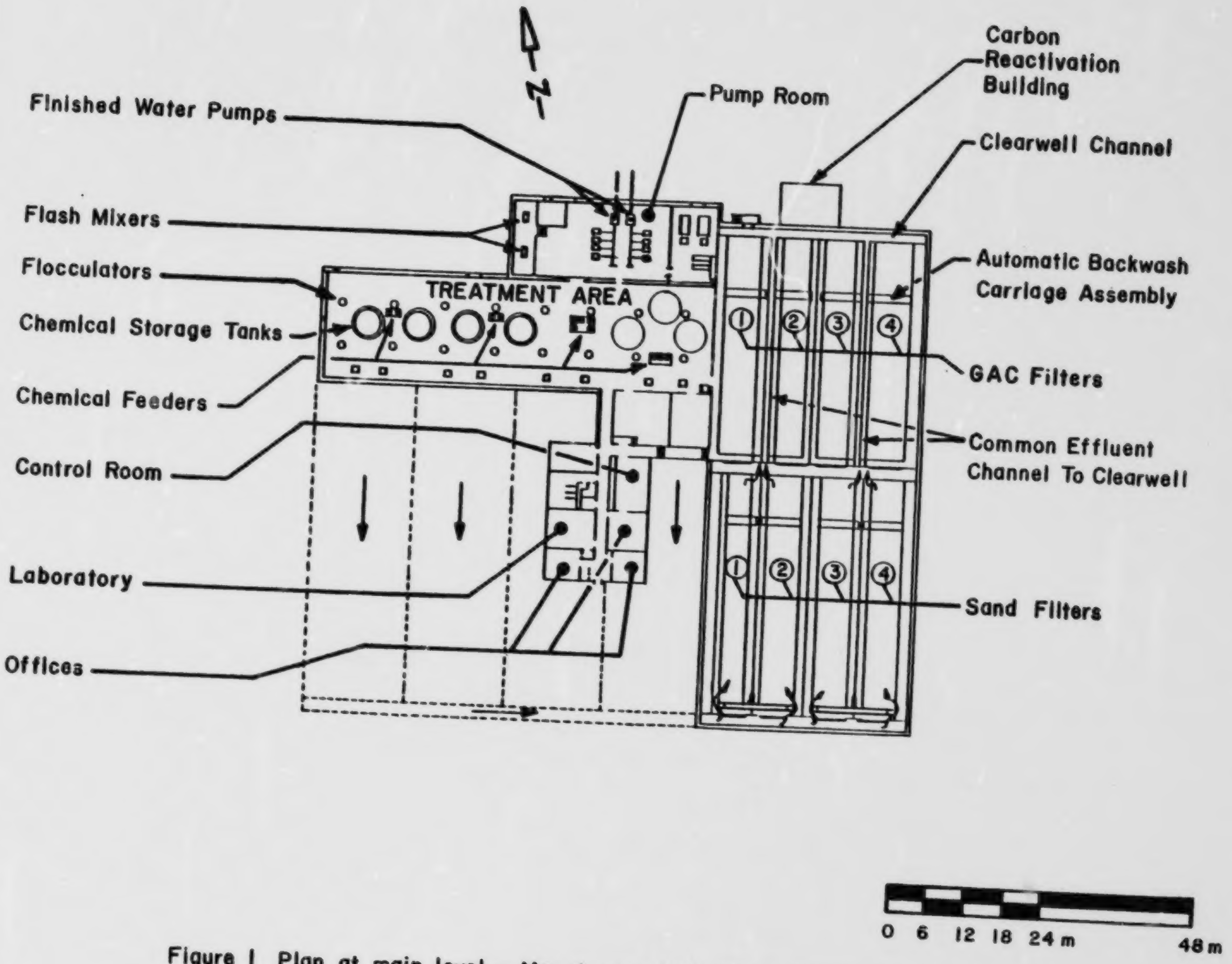

Finished Water Pumps
Flash Mixers
Flocculators
Chemical Storage Tanks
Chemical Feeders
Control Room
Laboratory
Offices
N
Pump Room
TREATMENT AREA
Carbon Reactivation Building
Clearwell Channel
Automatic Backwash Carriage Assembly
GAC Filters
Common Effluent Channel To Clearwell
Sand Filters
①
②
③
④
0 6 12 18 24 m 48 m

Figure 1 Plan at main level — Manchester, N.H. Water Treatment Plant.

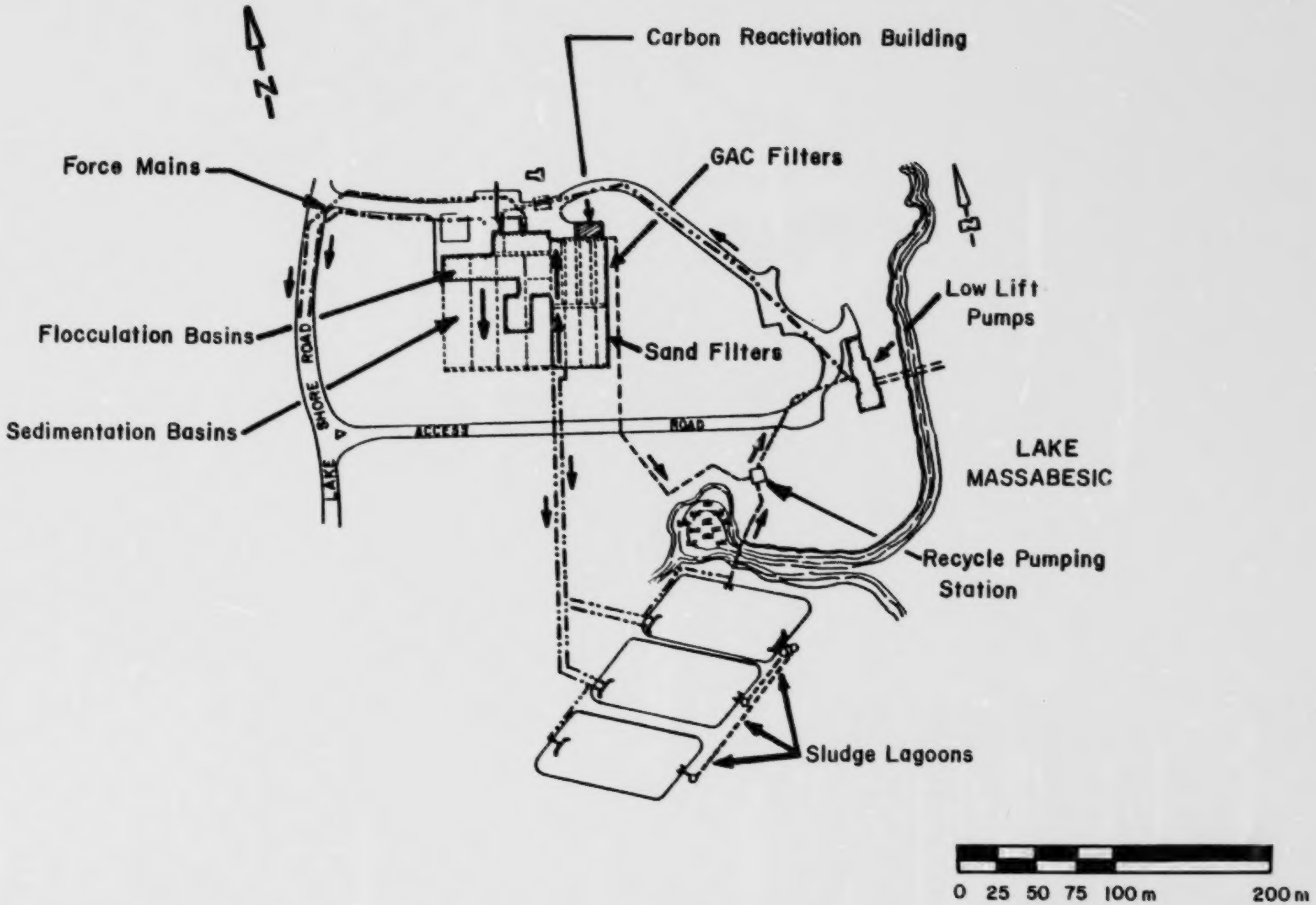

Carbon Reactivation Building
GAC Filters
Force Mains
Low Lift Pumps
Flocculation Basins
Sand Filters
Sedimentation Basins
ACCESS ROAD
LAKE SHORE ROAD
LAKE MASSABESIC
Recycle Pumping Station
Sludge Lagoons
N
0 25 50 75 100 m 200 m

Figure 2 Site Plan — Manchester, N. H. Water Treatment Plant.

TABLE 1

UNIT PROCESS DESIGN
MANCHESTER WATER TREATMENT PLANT

Item	Description
General	
Average Daily Flow	4.94 x 10^4 m^3/day (13.0 MGD)
Maximum Hydraulic Flow	1.52 x 10^5 m^3/day (40.0 MGD)
Rapid Mixing	
Number of Basins	2
Dimensions Each	3.66m x 3.66m x 2.13m W.D. (12' x 12' x 7' W.D.)
Number of Mixers	2
Detention Time at Average Flow	1 min. 40 sec.
Detention Time at Maximum Flow	32 seconds
Liquid Volume (Total)	57.1m^3 or 57,084 liters (15,080 gals.)
Speed	Fixed - 45 rpm
Flocculation	
Number of Basins	4
Dimensions of Each	15.24m x 15.24m x 3.35m W.D. (50' x 50' x 11' W.D.)
Number of Flocculators Per Tank	4
Liquid Volume Each	778.7m^3 or 778,659 liters (205,700 gals.)
Detention Time at Average Flow	80 minutes
Detention Time at Maximum Flow	30 minutes
Mixers (Speed)	Vertical - (Variable 1/2 to 21 rpm)
Sedimentation	
Number of Basins	4
Dimensions Each	15.24m x 51.21m x 3.35m W.D. (50' x 168' x 11' W.D.)
Liquid Volume Each	2,619.7m^3 or 2,619,505 liters (692,000 gals.)
Overflow Rate at Average Flow	1.52m/hour (893 gpd/ft^2)
Overflow Rate at Maximum Flow	2.02m/hour (1,190 gpd/ft^2)
Detention Time at Average Flow	5.00 hours
Detention Time at Maximum Flow	1.65 hours
Sludge Removal Mechanisms	Each basin

(Continued)

Table 1 (Continued)

Item	Description
Flow-Through Velocity at Average	0.39m/min. (1.28 ft/min)
Sand Filtration	
Number of Units	4
Dimensions Each	4.88m x 33.53m (16' x 110')
Surface Area Each	163.5m^2 (1,760 ft^2)
Surface Loading at Average	3.18m/hour (1.3 gpm/ft^2)
Surface Loading at Maximum	9.78m/hour (4.0 gpm/ft^2)
Media	Silica Sand
Media Depth	27.94cm (11")
Media Size	0.55 to 0.65 mm
Raw Material	1.5 uniformity coefficient
Backwash	Automatic - Backwashing on head loss criteria
Clearwell	
Number of Units	1
Volume	1,836m^3 or 1,835,925 liters (485,000 gals.)
Carbon Filtration (Operational)	
Number of Units	4
Dimensions Each	4.88m x 33.53m (16' x 110')
Surface Area Each	163.5m^2 (1,760 ft^2)
Surface Loading at Average	3.18m/hour (1.3 gpm/ft^2)
Surface Loading at Maximum	9.78m/hour (4.0 gpm/ft^2)
Media	Granular Activated Carbon - (Coal Base)
Media Depth	121.9cm (48")
Media Size	8 x 30 mesh
Backwash	Automatic - Backwashing on head loss criteria
Empty Bed Contact Time at Average Daily Flow	23 minutes 4.94 x 10^4 m^3/day (13.0 MGD)

TABLE 2

TYPICAL ANALYSIS OF RAW AND TREATED WATER MANCHESTER WATER WORKS

Parameter	Unit	Raw Lake Water	Finished Water
Alkalinity	mg/L $CaCO_3$	3.0	4.0
Aluminum	mg/L	0.05	0.06
Calcium	mg/L	3.6	3.6
Chloride	mg/L	17.0	17.0
Copper	mg/L	0.1	0.1
Hardness	mg/L $CaCO_3$	11.6	11.6
Iron	mg/L	0.05	0.01
Magnesium	mg/L	0.7	0.7
Manganese	mg/L	0.05	0.03
Phosphate (Total)	mg/L	0.10	0.80
Suspended Solids	mg/L	4.0	1.5
Settleable Solids	mg/L	0.0	0.0
Total Dissolved Solids	mg/L	40.0	35.0
Sodium	mg/L	9.2	11.0
Potassium	mg/L	0.5	0.5
Silica	mg/L	1.7	1.2
Sulfates	mg/L	6.0	12.0
Total Organic Carbon	mg/L	4.2	1.8
Color - Apparent		10.0	1.0
pH		6.5	7.1
Specific Conductance	uMho	90.0	110.0
Residual Chlorine	mg/L	0.0	0.2

NOTE: Analysis conducted by Manchester Water Works and the NH Water Supply and Pollution Control Commission.

SECTION 5

FLUID-BED REACTIVATION AND CARBON TRANSPORT PROCESSES

General

Operation of the GAC treatment and reactivation system at the Manchester Water Treatment Plant involved the use of 4 existing GAC filters, a fluidized-bed carbon reactivation furnace and 4 hydraulic transport carbon mechanisms during the research period. Each of the filters measures 4.88 meters (16 feet) wide by 33.53 meters (110 feet) long, and contains a 1.22 meter (4 feet) depth of 8 x 30 mesh-size coal base carbon. The filter loading rate at average daily flow is about 1.61 x 10^2 $m^3/min/m^2$ (1.3 gpm/ft^2) and the empty bed contact time at this rate is about 23 minutes.

Each of the 4 carbon filter backwash carriages at the plant was completely retrofitted with equipment designed to permit semiautomatic exchange of the GAC between the filter room and the reactivation building. The fluid-bed reactivator was housed in a new brick and block masonry structure, located on the north side of the filter building. The reactivation furnace was designed and manufactured by Westvaco, Charleston, SC, and has a rated capacity of 226.8 kilograms (500 pounds) of GAC throughput per hour. The major components of the furnace include a spent GAC storage tank, dewatering screw, reactivation furnace, quench tank, reactivated GAC storage tank, steam generator, air compressor, and instrument control panel. The furnace is divided into 4 temperature zones: drying zone, incineration zone, reactivation zone, and combustion zone.

Fluid-Bed Reactivation Process

The reactivation furnace (Figure 3) is approximately 6.86 meters (22½ feet) tall and 2.13 meters (7 feet) in diameter at its widest point. The 0.635 centimeter (quarter-inch) outer steel shell is covered with a cast-in-place refractory lining up to 35.56 centimeters (14 inches) in thickness. The reactivation process consists of the GAC being vertically processed through the reactivator in a counter flow direction to the rising hot gasses which dry the carbon and subsequently volatize and pyrolyze the adsorbate.

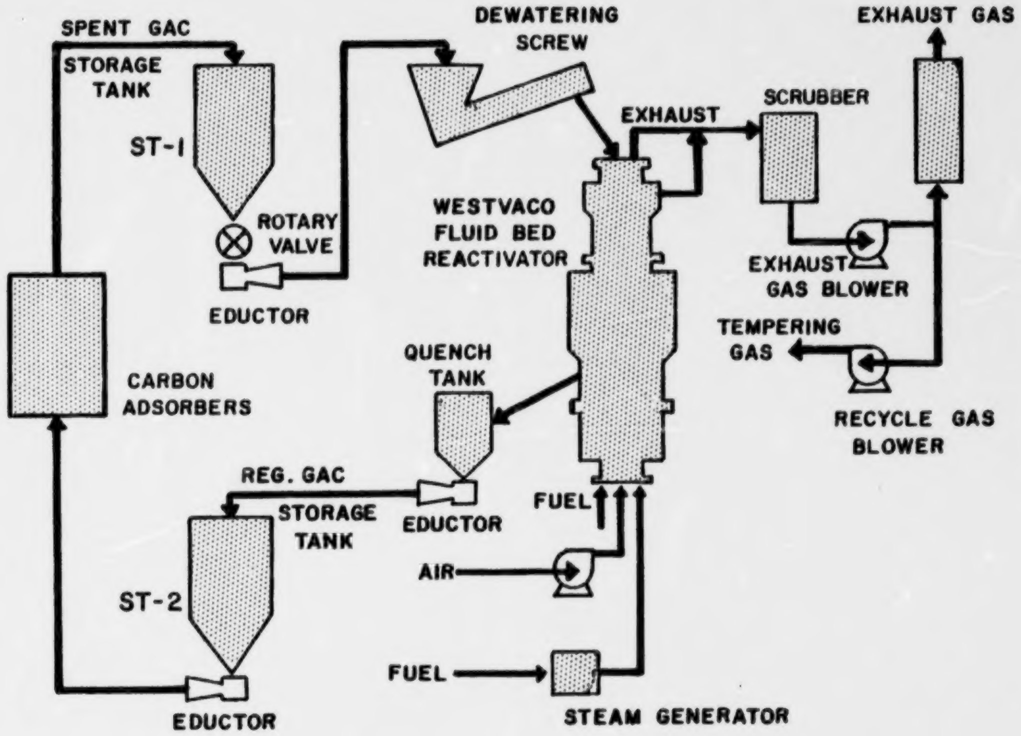

SPENT GAC
STORAGE TANK
ST-1
ROTARY VALVE
EDUCTOR
DEWATERING SCREW
WESTVACO FLUID BED REACTIVATOR
EXHAUST
SCRUBBER
EXHAUST GAS
EXHAUST GAS BLOWER
TEMPERING GAS
RECYCLE GAS BLOWER
CARBON ADSORBERS
QUENCH TANK
REG. GAC
STORAGE TANK
EDUCTOR
FUEL
AIR
ST-2
FUEL
EDUCTOR
STEAM GENERATOR

Figure 3. Process flow for GAC reactivation system at Manchester, N.H.

Spent GAC is hydraulically educted from the filters and directed through carbon transport hoses to a 33.3 m^3 (8,800 gallon) capacity spent GAC storage tank. The carbon slurry is metered from the spent tank at a rate of about 226.8 kilograms (500 pounds) per hour through a rotary valve to an eductor and then to a dewatering feed screw located on the upper level of the reactivation building. At this point, the dewatered carbon is completely dried in the fluid bed drying zone of the reactivator. The dryer is separated from the reactivator/incinerator by a stainless steel plate perforated with a pattern of drilled holes to distribute the gas flow for uniform fluidization of the carbon bed. The gas flow through this chamber is induced by the suction of a fan, creating a negative pressure within the chamber. The temperature within the dryer zone is approximately 149°C (300°F). A portion of the reactivation off-gas is tempered in the dryer plenum with recycled gas being used to dry the wet spent carbon. The remainder of the off-gasses are vented to the atmosphere.

The dried spent GAC then passes from the drying zone through a discharge pipe and rotary metering valve to the reactivation zone of the furnace. The rotary valve also serves to isolate the 2 pressure zones within the reactivation process. The reactivation zone is separated from the combustion zone or chamber by a stainless steel plate fitted with a number of nozzles which distribute the gasses uniformly over the cross section of the furnace. A series of horizontal baffles also rest on the plate to assure sufficient GAC residence time and temperature averaging 30 minutes at 816°C (1500°F). In this lower section, part of the adsorbate is volatized from the GAC while the remaining pyrolyzed portion is removed by selective reaction with steam to form hydrogen and carbon monoxide. As the gas passes through the GAC bed, heat is transferred to the GAC to raise the temperature in order to volatize the adsorbed organics. The carbon adsorbate is then further combusted or pyrolyzed in the incineration zone directly above the reactivation bed. Excess gas from incineration is bypassed and mixed with off-gas from the dryer, and the system gas is treated in a 3-stage venturi type scrubber to remove particulate matter before discharge through an exhaust stack to the atmosphere. Reactivated GAC is then finally discharged from the reactivation zone to a quench tank where it is cooled before eduction to the reactivated GAC storage tank of 33.3 m^3 (8,800 gallon) capacity and returned by eduction to the filters.

The bottom section of the furnace or combustion chamber utilizes a balanced stream of fuel and oxygen to control the quality of combustion gasses in the fluidizing medium. Steam is also injected into this chamber to provide an additional flow of fluidizing gasses and to temper combustion chamber temperatures. The energy for the carbon reactivator and the steam generator unit is supplied by combustion of #2 fuel oil. About

60% of the fuel is consumed by the reactivator and the remaining 40% is used for steam production. The temperature in the combustion chamber is about 1038°C (1900°F).

The reactivation process is fully instrumented and controlled by a main reactivation control console located in the reactivation building and a remote control console located in the control room of the water treatment plant. The remote control provides essential monitoring functions plus an alarm function and emergency stop capability. There are many safety features designed into the reactivation system to protect operating personnel and equipment. For example, excess pressures that might be generated by an uncontrolled atmosphere in the reactivator are relieved by one of several safety devices. These include a blowout panel between the dryer chamber and the relief stack, a secondary blowout panel between the reactivator and incineration chamber, and a water-sealed section below the combustion chamber.

Carbon Transport Process

Each of the 4 GAC filters at the Manchester Water Treatment Plant were completely retrofitted with semiautomatic GAC eduction mechanisms that were designed to permit exchange of filter media between the plant filter room and reactivation building. A 3-dimensional drawing of the carbon filter carriage and semiautomatic carbon transport mechanism is presented in Figure 4. The equipment consisted of a collection and distribution mechanism, hoist mechanism, eductor piping system, fluid transport system, pressure supply system, and control system. The intended purpose of the system was to remove and subsequently replace 1.81 m^3 (64 ft^3) of GAC from each of the individual filter cells with the remaining cells still in service. A pair of stainless steel header and riser pipes were lowered into the cell during the removal cycle and then raised during the fill cycle by a single operator stationed on the filter backwash carriage. The GAC transport system was activated by energizing the travelling bridge motor, backwash pump motor and washwater pump motor. If the travelling bridge was not directly over a cell, it would automatically move to that position. The filters' backwash pump was always in the "on" position during the removal cycle in order to fluidize the carbon media in the filter cell. Once proper pressure was achieved in the control line, the manual control valve on the eductor supply could be opened and the pressure control valve closed to obtain the desired operating pressure.

Electrically operated solenoid valves initiated water flow to the eductors. A manual safety catch was released by the operator allowing the headers to free-fall into the GAC media. GAC was transported through a hose conveyor system called a power track which consisted of 4-5.08 centimeter (2-inch)

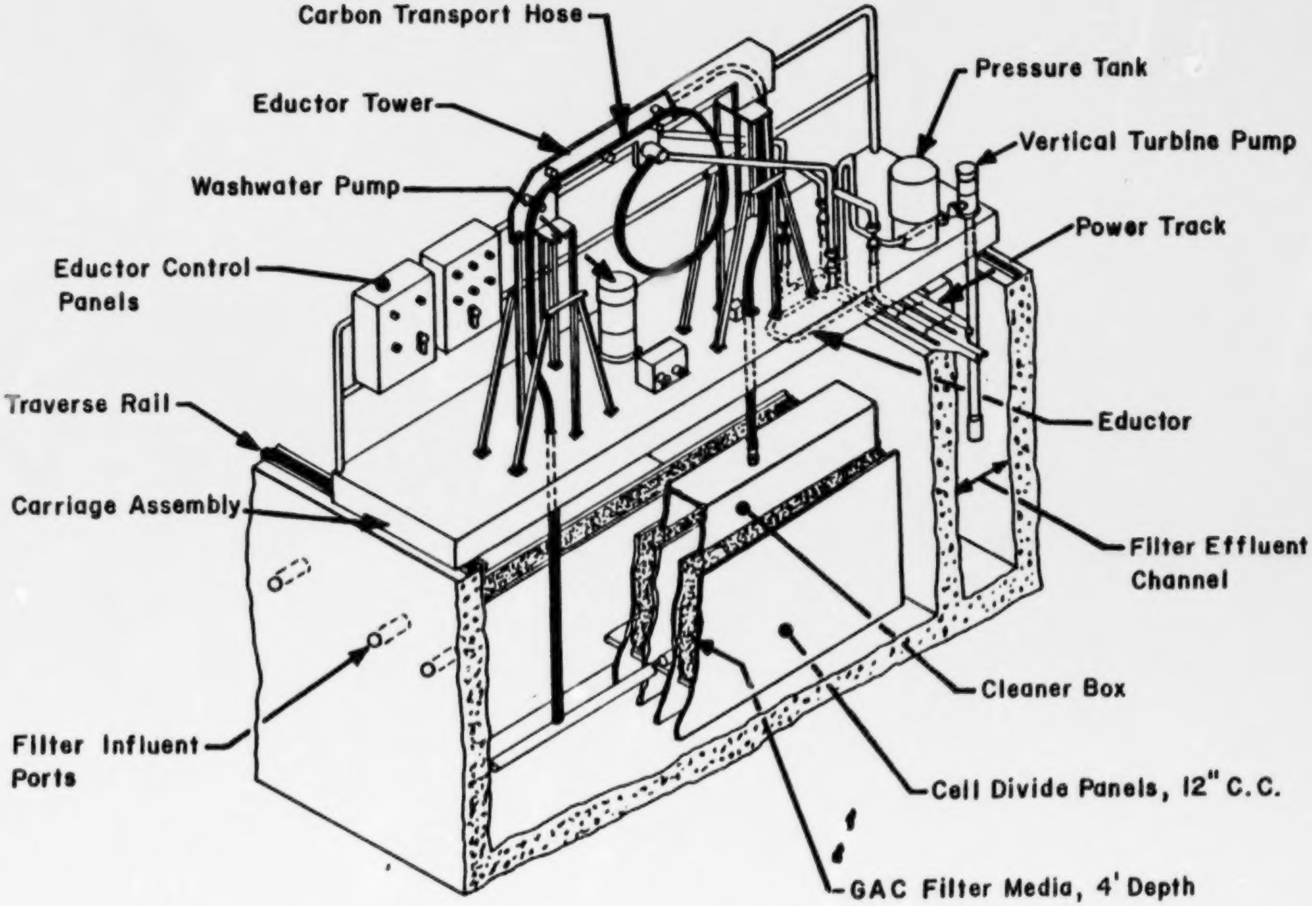

Carbon Transport Hose
Eductor Tower
Washwater Pump
Eductor Control Panels
Traverse Rail
Carriage Assembly
Filter Influent Ports
Pressure Tank
Vertical Turbine Pump
Power Track
Eductor
Filter Effluent Channel
Cleaner Box
Cell Divide Panels, 12" C.C.
GAC Filter Media, 4' Depth

Figure 4. Layout for GAC transport system (semiautomatic operation).

flexible PVC hoses. Transport velocities through the hoses ranged from 0.91 to 1.52 m (3 to 5 Ft) per second. One pair of hoses was used for carbon removal and the other pair for carbon replacement. The power-track assembly provided a smooth transition between the hose carrier and travelling backwash mechanism as it moved from one end of the filter to the other and it prevented the hoses from exceeding their maximum bending radius. A second set of pipes and hoses connected the filter hoses to the eductors for returning reactivated GAC to the filters. These were located in the reactivation building at the base of the reactivated GAC carbon storage tank.

Once the GAC was removed from a filter cell, the mechanism was reversed to fill the cell. In this mode of operation, the headers moved vertically inside the cell at a controlled rate and when reaching the top of the cell, the fill cycle automatically stopped. The carriage was then positioned over the next cell and upon reaching the cell, the travelling bridge automatically stopped. The cycle was then repeated in each filter cell until the entire filter volume was reactivated.

SECTION 6

PROJECT OVERVIEW

Since the GAC research project spanned a period of nearly 5 years (July 1977 to April 1982), project work was subdivided into 3 main investigative phases. Major objectives of the Phase I work involved the design, construction and startup operation of the GAC fluid-bed reactivation system and semiautomatic GAC transport system. Also included was the establishment of analytical capabilities at the treatment facility to monitor GAC performance. Phase II of the project was dedicated to conducting research work on both systems to evaluate their individual cost and performance. An important secondary effort during the Phase II period was the investigation of GAC losses resulting from reactivation and transport. Phase III was undertaken to study the costs and feasibility of utilizing the Manchester fluid-bed furnace as a regional reactivation facility. The contents of this report are presented in the chronological sequence mentioned above and are shown in summary form in Table 3.

Note that both the GAC reactivation furnace and the semiautomatic GAC transport mechanisms were prototype pieces of equipment. At the time of equipment startup in June 1979, the fluid-bed reactivator at Manchester was only the third full-scale size unit of its kind in operation within this country. In the case of the semiautomatic transport equipment, the Manchester installation was the first of its kind anywhere in the world. Administrative and operating personnel at Manchester spent a great deal of project time resolving problems, and for this reason a significant portion of this report is devoted to their identification and solution. The intent of the authors is not to over emphasize their problems, but rather to discuss their solution in sufficient detail for the purpose of minimizing repeat experiences at other locations.

TABLE 3

CHRONOLOGY OF FLUID-BED REACTIVATION PROJECT
MANCHESTER WATER WORKS, MANCHESTER, NEW HAMPSHIRE

Item	Month	Year
Bench Scale Reactivation Test Program	March	1977
Manchester Awarded USEPA Research Grant	July	1977
Design and Equipment Contracts Awarded (Phase I)		
Carbon Transport System (CTS)	October	1977
Carbon Reactivation Building	December	1977
Fluid-Bed Reactivation System (FBR)	January	1978
Construction Contract Awarded	July	1978
Construction Began (Phase I)	August	1978
Reactivation and Transportation Equipment Installed (Phase I)	January	1979
Construction Completed	May	1979
First Performance Run	June	1979
Shakedown Period	July-December	1979
Second Performance Run and Startup of Research Program (Phase II)	January	1980
Research Program (Phase II) Completed	May	1981
Preliminary Investigation of Regional Reactivation Program (Phase III)	June-October	1981
Startup of Regional Reactivation Program (Phase III)	November	1981
Regional Reactivation Program (Phase III) Completed	December	1981
MWW Reactivation Research Program Completed (Phase I, II, III)	April	1982
Preparation of Research Project Report	May-November	1982

SECTION 7

PHASE I: GAC REACTIVATION SYSTEM DESIGN, CONSTRUCTION, AND OPERATION

Purpose and Scope - Phase I

1. To design, construct and operate a fluid-bed carbon reactivation system.
2. To design, construct and operate a semiautomatic GAC transport system.
3. To provide analytical capabilities to monitor GAC performance.

Design and Construction Program - Phase I

The design of the carbon reactivation system began in late 1977. Three consultants were involved: Whitman & Howard, Inc. of Wellesley, MA, who was responsible for coordination of overall system design plus design of the building structure for the fluid-bed reactivation equipment; Westvaco Corp. of Charleston, SC, who designed and furnished the fluid-bed furnace and related equipment; and Environmental Elements Corp. of Baltimore, MD, who designed and furnished the carbon transport mechanisms for each of the 4 existing GAC filters.

The fluid-bed reactivation system was designed to handle a wide range of operating conditions due to expected changes in future water quality and flow. Organic matter from the existing supply contained natural humic substances while a future supply source contained both humic matter and some man-made volatile organics. An organic loading of 0.045 to 0.068 Kg/Kg (0.1 to 0.15 Lb/Lb) of adsorbate was selected for design along with a 3-month optimum reactivation frequency, and a 226.8 Kg (500 Lb) per hour capacity furnace. Other design considerations included a review of USEPA publications for the design of GAC reactivation facilities.

One of the most important design goals for the GAC reactivation system was the minimization of carbon losses due to abrasion. Wide sweeping elbows were selected and installed at all changes in piping direction each with a minimum bend radius of 5 times the pipe diameter. A maximum carbon transport velocity of 1.524m (5 Ft) per second was also established for the piping layout design.

Upon completion of design documents, bids were opened in July 1978 for the construction of a concrete and masonry building addition to the north wall of the existing water treatment plant filter room. This construction contract included the installation of the reactivation equipment and transport equipment obtained directly from the manufacturers by the Manchester Water Works. The base price for the 10.36 m (34 Ft) by 11.89 m (39 Ft), three-level building structure plus acquisition and installation of the reactivation and transport equipment amounted to $875,500. Construction of the reactivator building began in August 1978 and was substantially completed by the end of the year. Installation of the fluid-bed reactivation system and carbon transport equipment continued throughout the winter, and contract work was finalized in May 1979.

Late equipment deliveries and incorrectly fabricated parts caused installation of all equipment to proceed extremely slow. Thus in order to expedite construction, considerable field engineering and field modification work had to be performed. A more detailed description of actual construction progress is shown in Table 3.

Following construction, the refractory lining of the fluid bed furnace was heat cured and a series of shakedown tests were performed on all systems to determine their reliability and degree of compliance with contract conditions. Throughout this testing period, a total of 6, 8-hour operator training sessions were conducted to familiarize the water treatment operations staff with maintenance and operating requirements of all equipment. Troubleshooting equipment problems and theory of operation was stressed throughout the training sessions. Each operator was given a detailed operations manual to be used as a learning aid as well as a reference source during actual operations. The training sessions were conducted by Westvaco engineers and technicians, and continued through the startup phase of the project.

Analytical Program - Phase I

During Phase I, the MWW laboratory personnel purchased, set up and received instruction in the use of new laboratory equipment. This equipment consisted of a Dohrman DC-54 TOC Analyzer, Perkin - Elmer Sigma I Gas Chromatograph which is used for trihalomethane analysis, and various pieces of apparatus employed in the routine evaluation of GAC performance (Table 4).

Start-up experiences with this equipment were generally good with the exception of the TOC analyzer. There were

TABLE 4

PHASE I - LABORATORY EQUIPMENT PURCHASES MANCHESTER WATER WORKS

Date of Purchase	Equipment Purchased - Reagents	Lab Analysis to be Performed	Amount
January 1978	Dohrman DC-54 TOC Analyzer	Total Organic Carbon	$ 16,000.
July 1978	Perkin-Elmer Sigma I Gas Chromatograph	Trihalomethanes Via Solvent Extraction	17,500.
August 1978	Riffle Sampler	Iodine and Phenol Number Analysis	100.
	Carrier Gases and Reagents	TOC and Gas Chromatography Analyses	1,000.
September 1978	Spex Model Mill Model #800-1	Iodine, Phenol Number Analyses	900.
	Ro-Tap Sieve Shaker, Sieves	Dry Sieve Analyses	1,000.
	Quebec Colony Counter	Standard Plate Analysis	200.
	Amperometric Titrimeter	Free and Combined Chlorine Residual	900.
November 1978	Test Filter Sampling Systems and Pumps	Test Filter Water Quality Analyses	800.
		TOTAL COST	$ 38,400.

numerous problems with this instrument which were ultimately resolved by considerable factory field service. These problems included failures in the electronic system and inconsistent operation of solenoid operated valves. Some minor difficulties were experienced in the start-up operation of the gas chromatograph. These difficulties were attributed to a lack of familiarity with the integrator and the specific programming function required to develop a program to perform the liquid/liquid extraction THM analysis. The other equipment purchased and setup included a Ro-Tap Sieve Shaker, Spex Mixing Mill, Quebec Counter, and Amperometric Titrimeter. Also during this time period, the test filter sampling system was installed by water treatment plant personnel. Phase I analytical work was not intended to develop research data but rather to acquire the capability of performing analyses with a high degree of precision and accuracy.

Reactivator Performance Tests and Operation - Phase I

Upon completion of operator training, the first full-scale test of reactivator performance was conducted over a 24-hour test period on June 2, 1979. This test was performed to compare design operating projections to actual operating results as well as to evaluate the conditions of the guarantee. Results of this test revealed a volumetric loss of 13.6% due to reactivation only (Table 6), and raised many questions regarding actual versus estimated carbon losses with the reactivator equipment. Additionally, the test revealed that the reactivator manufacturer would have to resolve a number of equipment problems prior to final acceptance by MWW. A summary of the problems encountered is shown in Table 5.

During the initial 7-month shakedown period, Manchester continued operating the reactivator while also working with the Westvaco Corp. engineers to resolve start-up problems previously mentioned (Table 5). These problems could be described as minor in nature and, for the most part, a solution to each problem was found within a reasonable time period. However, the nuisance aspect of these minor problems was far outweighed by the fact that they were frequent and continually interrupted reactivator operation.

In September 1979, a major problem occurred with the 33.3m^3 (8,800 gallon) spent carbon storage tank. Over a period of just 4 months, the 304L stainless steel in the spent GAC storage tank developed a large number of small pinhole leaks in the upper half of the cone section and substantial pitting over the remaining interior surface of the vessel. Inspection of both the spent and reactivated GAC storage tanks revealed that the problem had occurred only in the spent GAC storage tank. Investigation by Westvaco Corp. resulted in a metallurgist's opinion that the corrosion problem was most likely due to the presence of organic chlorides in the spent carbon media. No definitive reason for

TABLE 5

ROUTINE REACTIVATOR PROBLEMS

These problems occurred as a result of mechanical and/or electrical malfunctions in the various equipment components.

A. Steam generator broke down.+
B. Air compressor failed.+
C. Fuel pump broke down.+
D. Carbon built up (coke) on reactivator burner.
E. Deterioration of gasket material on exhaust vent.
F. Exhaust and recycle gas blowers broke down.+
    1. Fan blades loosened at shaft.
    2. Carbon frequently built up on fan blades.
    3. Bearings frequently failed.
G. Scrubber system plugged with carbon material.+
H. Dryer cooling water spray nozzles blocked with carbon material.+
I. Occlusion of carbon quench tank outlet.
J. Frequent spalling of refractory lining.+
K. Plugged reactivator and dryer gas distribution plates.+
L. Pitted stainless steel caused gas leaks.
M. Pneumatic control valves malfunctioned.+
N. Rotary valves broke down.
O. Condensate tank float system failed.
P. Sight glasses cracked; caused gas leaks.
Q. Flame safety system failed.+
R. Solenoid valves malfunctioned.+
S. Eductors plugged with carbon.
T. Instrumentation.+
    1. Faulty thermocouple.
    2. Fuel flow transmitter malfunctioned.
    3. Oxygen analyzer failed.
    4. Differential pressure indicators failed.
    5. Current to pneumatic transducers failed.
    6. Temperature controllers malfunctioned.
    7. Transmitters broke down.

+ Malfunction of system component would often lead to reactivator shutdown.

TABLE 6

SUMMARY DATA FOR FLUID-BED PERFORMANCE CERTIFICATION RUNS

Parameter	Run 1	Run 2	Average	Design
Date	6/02/79 - 6/03/79	1/04/80 - 1/06/80		
Elapsed Time; Hours	24	54.5	39.25	
Spent GAC Feed Rate Kg/Hr (Lb/Hr)	256.2 (564.8)	293.0 (645.9)	274.6 (605.4)	247.2 (545.0)
Product Rate Kg/Hr (Lb/Hr)	223.1 (491.8)	255.8 (563.9)	239.5 (528.0)	220.0 (485.0)
Adsorbate Load Kg Ads./Kg GAC (Lb Ads./Lb GAC)	0.259 (0.117)	0.262 (0.117)	0.260 (0.118)	0.22-0.33 (0.1 -0.15)
Iodine Number mg/g	883	965	924	850 (min.)
Decolorizing Index D.I.U.	4.8	4.6	4.7	10 (max.)
GAC Losses Volumetric %	13.6	10.1	11.9	6 (max.)
Off-Gas Particulate Kg/Hr (Lb/Hr)		0.0454 (0.10)		0.785* (1.73)*

* NH Standard Maximum Value

the failure was ever found. Several methods of repairing the tank were evaluated and a decision was made to sandblast the tank and install a polyester fiberglass lining. This lining had a dry applied thickness of 0.3175 cm (125 mils) to 0.3302 cm (130 mils) in the top section and 0.38 cm (150 mils) to 0.508 cm (200 mils) in the bottom conical section. A silicon carbide compound was used in the lower cone section layers to reduce abrasion caused by the GAC.

The extent to which the polyester lining material might have been leaching into the vessel contents became a question that was subsequently investigated. An experiment was performed to evaluate the organic content of the water held in contact with the liner for 48 hours and then to compare those results to values found in system tap water. The qualitative findings of a GC mass spec analysis showed the development of predominant peaks for the following compounds (in order of elution): Styrene, 2-Ethoxy-Ethanol Acetate, Benzaldehyde, Dimethyl phthalate and Dibutyl phthalate.

The testing was performed on the spent lining both upon initial installation and in January 1980 after 5 months of service. The leaching of these compounds was not a major concern because the spent carbon storage tank precedes the reactivation process where these compounds are destroyed. After 2 years of service, the lining is still in excellent condition. Manchester's experience had demonstrated that 304L stainless steel ("L" signifies low carbon stainless steel) is less preferable than the higher grade stainless steel materials when used in a GAC application. Specifically, equipment and piping fabricated with 316L stainless steel displayed far greater durability than equipment and piping fabricated of 304L stainless steel under the same service conditions.

Another major problem encountered during the shakedown period involved the spalling of a portion of refractory lining in the dome section of the reactivator. Large pieces of refractory material dislodged from the dome and fell on to the reactivator gas distribution plate. In hopes of avoiding future problems, about 75% of the dome refractory lining was replaced.

By early January 1980, most of the major problems with the fluid-bed reactivator equipment had been resolved, and Manchester had reactivated over 0.272 million Kg (300 tons) of GAC. A second performance test run was then conducted for 2 reasons. The first reason was to reconfirm the magnitude of the loss value experienced in the first run, and the second reason was to have the reactivator manufacturer resolve the numerous minor problems with the equipment prior to final acceptance by the MWW. Both of these tests were jointly conducted by MWW personnel and Westvaco Corp. engineers with the exception of the stack emissions analysis which was performed by Environmental

Research and Technology, Inc. of Cambridge, MA. Table 6 shows the data obtained from each of the 2 performance runs and indicates that the reactivator met or exceeded all design values except for carbon losses. The average volumetric carbon loss through the reactivator equipment only for the 2 performance runs was 11.9% versus the originally projected 6% value.

Carbon Transport Equipment Operation - Phase I

The carbon transport system was designed to accomplish 4 basic objectives: 1) To reduce operating and labor costs; 2) To provide improved process control; 3) To reduce system losses; and 4) To provide maximum utilization of the existing equipment. Unfortunately, none of these objectives was ever achieved. The carbon transport equipment presented numerous problems, many of which are described in Table 7.

Operational problems with the semiautomatic GAC transport system contributed to an extreme lack of equipment reliability, excessive maintenance, and unacceptable media removal from the filter beds. The equipment was troubled by constant mainteance problems, resulting in substantial downtime. Approximately 2 hours of maintenance was required for every hour of actual equipment operation. When the transport mechanism did work, it was capable of removing only about 75% of the media in the 122 cm (48-in) carbon bed.

The carbon transport equipment manufacturer was asked to review the equipment problems and submit a proposal describing any improvements or modifications necessary to have the equipment perform at a reliable level of operation. The projected cost to improve one of the filter mechanisms was in excess of $22,000 which was not covered in the research budget. Therefore, use of this equipment was discontinued and it was dismantled and removed from the treatment facility. The staff at the MWW feels that the concept and purpose of the semiautomatic carbon transport is sound and with required design modifications, a high degree of reliability and efficiency could be achieved.

The most effective method found for transporting carbon between the filters and the reactivator was with the use of a 7.62 cm (3-in) eductor and 7.62 cm (3-in) transport polyvinyl hose, hereafter referred to as the manual eductor and hose GAC transport system (Figure 5).

This transport method required the operator to position himself on planking at the top of the carbon media and using a 5.08 cm (2-in) handheld polyvinyl hose (Figure 5), remove the GAC. With a 379.2 KPa (55 psi) motive water pressure to the influent of the eductor, an operator can transport approximately 907.2 Kg (2,000 Lbs) of GAC in about 20 to 25 minutes. The operator was able to remove 100% of the GAC from

TABLE 7

CARBON TRANSPORT EQUIPMENT PROBLEMS

1. Power track cables failed.
2. Header cables failed.
3. Power track cadmium plated chains severely corroded.
4. Headers contacted cell divider plates preventing penetration into carbon media.
5. Proper alignment between the backwash port and header assembly was difficult to achieve.
6. Clutches on hoist motors failed.
7. Bladder tanks failed.
8. Pressure switches required adjustment.
9. Indexing switches required adjustment.
10. Heater overload protectors in control console failed.
11. Pinch valves failed.
12. Pulleys on header cables failed.
13. Cell positioner system failed causing nonrepetitive misalignment.
14. Solenoid valves failed.
15. Relay switches failed.
16. Header assembly hoses failed on roller guides.

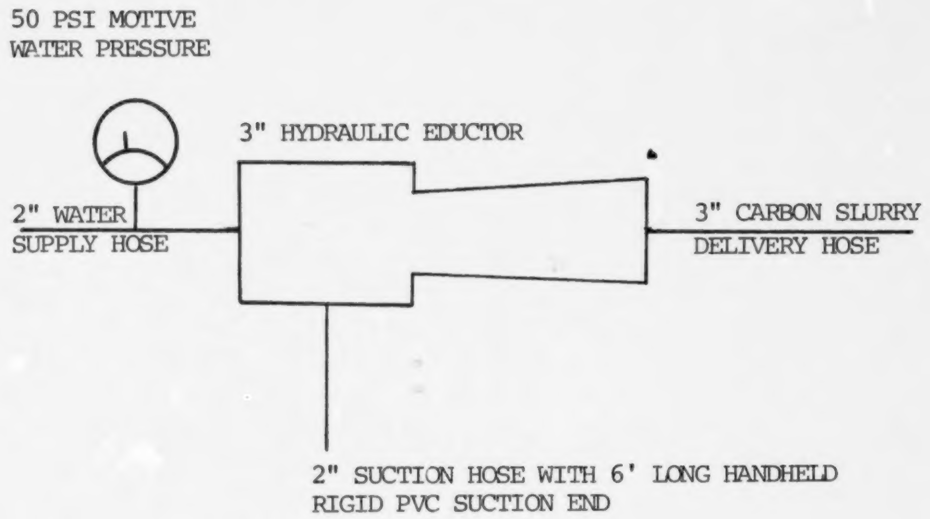

50 PSI MOTIVE
WATER PRESSURE
3" HYDRAULIC EDUCTOR
2" WATER
SUPPLY HOSE
3" CARBON SLURRY
DELIVERY HOSE
2" SUCTION HOSE WITH 6' LONG HANDHELD
RIGID PVC SUCTION END

Figure 5. Manual eductor and hose GAC transport system

each cell section of the filter. This method of transporting GAC was quick, simple, efficient, inexpensive and virtually maintenance free.

Cost Analysis - Phase I - Capital Construction Costs

Construction of the entire reactivator system was started in August 1978 and completed in May 1979 at a final installed cost of $1,022,300. A breakdown of this figure is shown in Table 8.

TABLE 8

PHASE I - CAPITAL COSTS
CARBON REACTIVATION SYSTEM IN MANCHESTER, NH
IN 1979

	Item	Cost
(a)	Carbon Reactivation Building	$ 226,900
(b)	Fluid-Bed System 226.8 kg/hr (500 lbs/hr) Capacity	528,600+
(c)	Carbon Transport System - 4 Filters	120,000+
(d)	Analytical Equipment (See page 24)	38,400
(e)	Analytical Supplies (Glassware, Lab, Gasses, Reagents, Etc.)	3,700
(f)	Contractual Services (Architectural & Engineering Fees for Building Design)	25,800
(g)	Personnel Costs (MWW)	22,300*
(h)	Virgin GAC for Test Filter	49,500
(i)	Material Testing Services	7,100
	TOTAL PHASE I COST	$1,022,300

+ Item (b) and (c) both include installation and equipment costs.

* Item (g) does not include overhead costs.

SECTION 8

PHASE II: GAC REACTIVATION AND TRANSPORT OPERATIONAL PROGRAM

Purpose and Scope - Phase II

1. To evaluate the cost and operating performance of a GAC reactivation system utilizing fluid-bed principles.

2. To evaluate the cost and operating performance of a semiautomatic carbon transport system.

3. To evaluate carbon losses resulting from reactivation and transport of GAC.

Reactivator Operational Research - Phase II

Many of the problems that occurred during the 2 performance tests and the following 7-month shakedown period continued in the Phase II Research Project. These problems contributed to excessive reactivator downtime. Through the first 14 months of operation, the uptime factor was only about 30%.

Additional measures had to be taken to improve the uptime operating efficiency of the reactivator. A reasonable uptime operating factor in the range of 70% to 75% was the ultimate goal. Therefore, a 7-step improvement program described below was implemented in August 1980. These measures were based on the recognition that quick response to maintenance problems is critical to a successful reactivator operation.

1. A complete inventory of all electrical and mechanical spare parts was ordered including motors, pumps, air compressor, valves, circuit boards, etc.

2. Instrumentation service capabilities were improved by instituting a service contract with Fischer & Porter Instrumentation Company. The contract required Fischer & Porter to respond to a service call within a 24-hour period.

3. The MWW would utilize whatever operational manpower overtime was required to expedite repairs to the equipment.

4. The MWW would utilize the outside services of welding, plumbing, motor repair shops, etc. should the work become too involved or the workload too excessive for plant personnel.

5. The MWW would assign one water treatment plant operator solely to the reactivator equipment for the duration of the research project. The responsibility of this individual would be to expedite and coordinate the reactivator operation including repairs, parts, inventory, required work force, etc.

6. The MWW would utilize the outside services of refractory lining repairmen to replace any major deficiencies in the refractory lining. (At the writing of this report, 2 major repairs and numerous minor repairs had been made to the refractory lining. The refractory presently appears to be in sound condition, although severely cracked.)

7. The Hercules Chemical Co. in Hattiesburg, Mississippi had reported a reactivator uptime factor in excess of 80%. Representatives from the MWW visited Hattiesburg and saw firsthand why and how Hercules was able to maintain a high operating factor, and then applied this knowledge to the Manchester reactivator.

Investigation of the Hattiesburg fluid-bed reactivation facility was very valuable in that it pointed out areas in the Manchester reactivation operation that could be improved. These improvements enhanced the efficiency of the operation as well as contributed to the improvement of the uptime factor of the equipment. There were 3 significant improvements that were made to the Manchester reactivator as a result of the Hattiesburg visit.

1. One of the frequent causes of the reactivator shutdown was mechanical or electrical failures in the steam generator. The Hattiesburg visit demonstrated that redundancy in the steam system would reduce the frequency of reactivator shutdown. Manchester, therefore, installed a secondary steam boiler that would automatically fire if the primary steam boiler failed.

2. Another major cause of reactivator shutdown was instrumentation failure. The Hattiesburg reactivator had the main instrumentation control panel located in a temperature controlled, dust-free building. The Manchester control panel was located in the center of the reactivator building without protection. To isolate the instruments from the hot dusty environment of the reactivator building, Manchester installed a prefabricated office around the main instrumentation control panel.

3. During the first few months of operation, Manchester experienced a fire in the dryer section of the reactivator. The Hattiesburg unit had also experienced fires early in their operation which required replacement of their dryer. These fires tend to stress and crack the stainless steel shell of the dryer. In anticipation of having to replace the dryer, Manchester purchased a spare dryer.

In the 3-month period following the implementation of all these improvements (the 7-step program plus improvements made as a result of the Hattiesburg visit) to the reactivator, Manchester was able to increase the uptime operating factor to 78%. The unit continued operating at a 75% to 80% uptime level for the next 10 months of operation until the termination of the research project. Through this 10-month period, the reactivator attained a level of operation that could be described as smooth and reliable. Obviously, the steps which were taken to increase the uptime operating factor proved very effective.

Carbon Loss Evaluation

From an economic standpoint, the most important area of the research project was that of carbon losses resulting from GAC reactivation and transport. Loss evaluations were conducted by 2 different methods and procedures: 1) Mass balance or percent loss by weight, and 2) Volumetric or percent loss by volume. Initial attempts at using the mass balance loss method were performed by quantifying the solids in the reactivator effluents. These analyses were also performed on individual furnace wastewater streams, and required the use of apparent water flow rates and the fluid-bed GAC production rate to arrive at a figure on percent loss by weight.

Carbon losses as measured by the mass balance method for the 2 reactivator performance tests were found to be 2.5 and 1.9%, respectively, compared to losses of 13.6 and 10.1% by volume for Test #1 and #2, respectively. Subsequently, the mass balance loss analysis was abandoned because it was felt that neither the data obtained nor the methods used in the analysis were valid indicators of actual carbon losses. Typical mass balance calculations are shown in Appendix A.

The validity of the mass balance measurements were considered questionable because of the difficulty in accounting for losses due to carbon burnoff in the reactivator, and losses incurred through backwashing the freshly reactivated GAC. Additionally, the changes in carbon volume as a result of bulk density and particle size changes could not be accounted for by the mass balance method. As a matter of practice, the water industry finds itself primary concerned with the volumetric levels of GAC in filter operation, and not the particular masses involved. In order for a GAC filter or contactor to properly operate at its design loading capacity, the void space or loss volume must be replenished with GAC media. Thus in order to produce a valid, workable volumetric procedure to evaluate GAC losses incurred through transport and reactivation, considerable time and effort was spent during the early stages of the Phase II research program.

Attempts at developing accurate and reproducible volumetric analyses were numerous and varied. These attempts ranged from a basic accounting of the makeup carbon purchased and installed to very carefully scrutinized analyses itemizing each individual loss because of transport and reactivation. The procedure that was finally developed for measuring and calculating volumetric carbon losses resulting from the reactivation and transport of GAC is shown in Appendix A.

In order to increase the accuracy of the above procedure, a good deal of attention was given to measuring carbon interface levels in the 2 carbon storage tanks (ST-1 and ST-2). Measurement techniques and calculation procedures were refined so that a repetitive and accurate volumetric loss could be obtained (see Appendix A.) Volumetric loss analyses were conducted through 5 reactivation cycles of the GAC to produce GAC loss trends or loss patterns. A summary of the volumetric loss data is depicted in Table 9. While the mass balance (percent by weight) method provided relatively consistent data, the values obtained were found to be substantially less than those derived from measurement on a volumetric basis. Initial measurements indicated a loss from the furnace of 13% by volume as compared to 2.5% or less by weight. A major problem with the volumetric method during the early stages was the unsatisfactory repeatability in making the carbon interface measurements in storage tanks ST-1 and ST-2. The initial volumetric analysis called for start and stop interface measurements made on both tanks producing 4 sets of measurements and 4 potential sources of error. Thus, during subsequent volumetric analysis, 2 of these measurements were eliminated by utilizing a full spent GAC tank and an empty reactivated GAC storage tank. The furnace was then operated until all of the spent carbon was reactivated and educted to the reactivated storage tank.

In an effort to provide a more repetitive and accurate measure of carbon interface, a number of different measuring devices were developed. The device which offered the greatest accuracy, sensitivity and ease of readout in minimum time was a telescoping fiberglass stadia rod fitted with a 20.3 cm (8 in) diameter flat metal base plate. Through statistical interpretations, the fiberglass stadia rod data obtained by 8 independent samplers on a given interface, provided the best overall reproducibility, accuracy and precision of measurement.

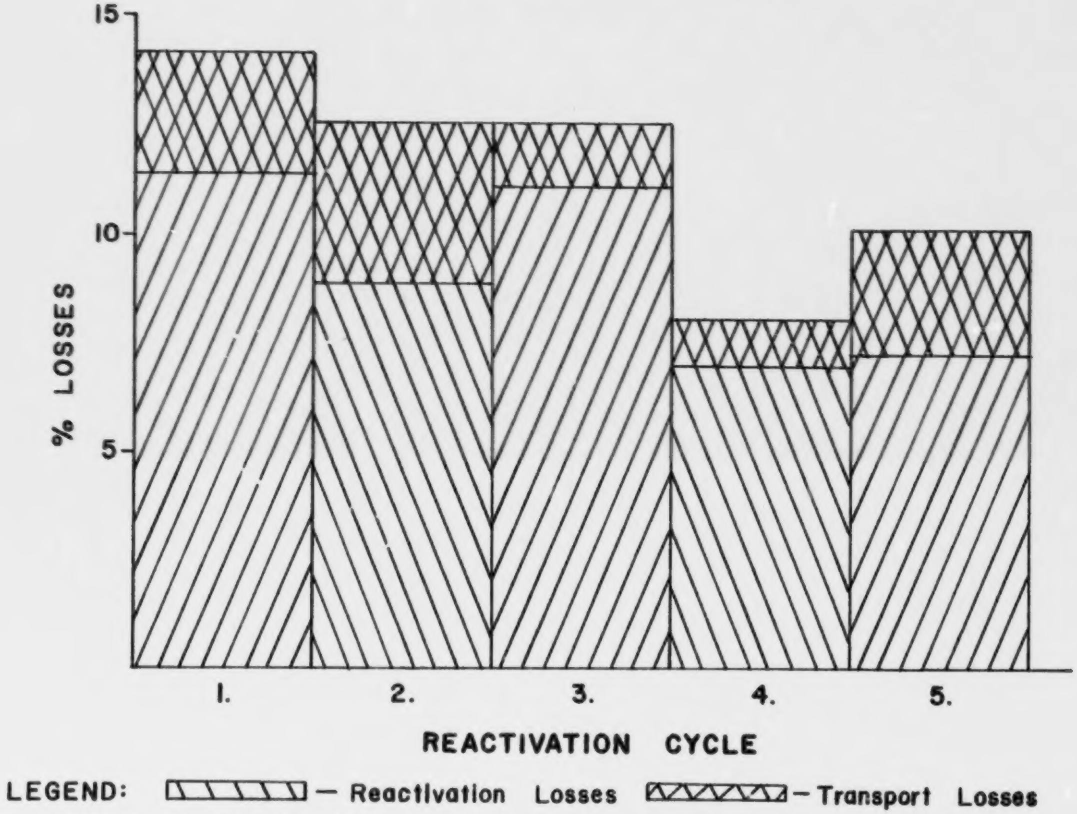
TABLE 9

VOLUMETRIC REACTIVATION & TRANSPORT GAC LOSSES

			LOSSES			
DATE	REACTIVATION CYCLE	TRANSPORT ONLY (%)	ROTARY* VALVE ONLY (C) (%)	DEWATERING* SCREW ONLY (C) (%)	REACTIVATION ONLY (%)	FILTER TO FILTER (D) (%)
01-24-79	1st				10.1^{B}	
06-02-79	1st				13.6^{A}	
08-15-80	1st					14.1^{B}
06-11-80	2nd				8.75^{B}	
08-15-80	2nd					10.6^{B}
02-13-81	2nd					14.2^{B}
09-29-80	3rd	6.73		5.2	11.0	14.8
02-13-81	3rd					10.0^{B}
02-09-81	4th	1.0	1.7	8.6	6.9	6.5
03-19-81	5th	2.9	3.2	7.25	___	10.1^{C}
AVERAGES		3.5	2.5	7.0	10.1	11.5

NOTE:
A. Procedure followed: Westvaco Volumetric Procedure (Appendix A)
B. Procedure followed: MWW Volumetric Loss Procedure #4 (Appendix A)
C. Procedure followed: MWW Volumetric Loss Procedure #5 (Appendix A)
D. Filter to filter loss values do not represent cumulative total of individual point loss analysis due to inherent errors in the accuracy of the analysis.

*Refer to Process Flow Diagram, Figure 107.



NOTE: Reactivation loss plus transport loss approximate overall filter to filter loss.

Figure 6. Summary of MWW GAC Volumetric Losses

Utilizing the stadia rod method, statistical deviations were found to be less than 1% of the measured volume. Additionally, measurements made from the GAC interface to the water surface level in the storage tank were found to be preferable to measurements made from the GAC interface to the cross-bracing structure at the top of the tank. This was due to the deflection of the cross-bracing caused by the weight of the individual standing on the bracing to conduct measurements. The cross-bracing consisted of 2, 2" x 2" x 1/4" steel angles providing reinforcement to the top portion of the tank. Measurements made to the water interface were more accurate since the water level in the tank remained fixed by an overflow weir.

In a further attempt to reduce the error in the volumetric analyses, agitation was maintained in each storage tank as the tank was being filled or emptied with GAC. Agitation was provided by a water nozzle located in the throat of the storage tank and was intended to minimize the bulk density variations thought to result from differences of tank fill rate, GAC particle size, and apparent density.

In the refinement of the volumetric analyses, various computational methods of integrating carbon interface volumes were explored. When filling a cylindrical vessel with GAC, such as ST-1 and ST-2, an inverted cone forms below the fill pipe. Consequently, there were various conical formulas applied to the calculation of the volume contained therein. A sectional integration method utilized by the Westvaco Corp. was used initially. Later, a method involving a best fit line technique was utilized to calculate carbon volume. The best fit method attempted to linerarize the slope of the GAC interface.

This method assumed a basic conical shape to the GAC interface in question. As such, any nonlinearities in the interface which did not occur as random deviations from a conical shape could potentially introduce error in the volume calculations. To eliminate this possibility, EPA proposed a method utilizing sectional frustrums to characterize the GAC water interface (Appendix A). By using 1-foot increments of the radius as frustrums, the nonradius irregularities of the GAC interface could be taken into account.

A summary of the loss analysis showed that the total volumetric losses decreased with each successive reactivation cycle. The trend of overall losses decreased from 14.1% on the first cycle to 10.1% on the fifth reactivation cycle. A complete summary of the loss procedures utilized are contained in the procedural section of this report.

Carbon Transport Equipment Operational Research - Phase II

As reported in Section 6 of this report, the excessive maintenance problems and lack of equipment reliability resulted in abandonment of the carbon transport equipment. The preferred eductor and hose system utilized in Phase I (Figure 5) continued through Phase II. This method of transporting carbon continued to work extremely well with little or no maintenance to the equipment.

COST ANALYSIS - PHASE II

Reactivation Research

Through the 2-year Phase II Research Program period, about 1.63 million kilograms (3.6 million pounds) of GAC was reactivated. Rather than develop a cost analysis based on 2 years of intermittent operation, it was decided that a more realistic analysis would be obtained from a period of steady state operation. The operational period selected was June 1980 to March 1981 which followed improvements made to the reactivator equipment. The reactivator uptime operating factor for this period was nearly 70%.

Table 10 shows a detailed breakdown of reactivation costs based on reactivation of 842,401 Kg (1,857,176 lbs) of GAC. It should be noted that all costs are based on actual expenses incurred during this time period. Also, the costs shown exclude that work which related to the research aspect of the project. The summary of the unit costs of reactivation presented in Table 10 are values based on the total costs presented in Table 11. Table 12 provides a detailed explanation of the reactivation cost items presented in Table 11.

Clearly demonstrated is the cost effectiveness of onsite GAC reactivation. Manchester was able to reactivate GAC during the period shown at a total cost of 47.9 ¢/Kg (21.7¢/Lb) versus purchasing virgin carbon at a cost of $1.36/Kg (61.5¢/Lb).

TABLE 10

MANCHESTER WATER WORKS
REACTIVATION COSTS
JUNE 1980 THROUGH MARCH 1981
BASED ON REACTIVATION OF 842,401 KGS (1,857,176 LBS) OF GAC

	Cost Item	Cost Per Kg	(Cost Per Lb)
A)	Makeup Carbon	15.59¢	(7.07¢)
B)	Labor for Reactivation	4.28	(1.94)
C)	Labor for Transportation	0.62	(0.28)
D)	Labor for Lab	0.11	(0.05)
E)	Labor for Administration	2.91	(1.32)
F)	Parts and Service Calls	5.87	(2.67)
G)	Fuel Oil	4.92	(2.23)
H)	Electrical Power	1.10	(0.50)
I)	Water	1.63	(0.74)
J)	Lab Supplies and Outside Analyses	0.11	(0.05)
K)	Depreciation	4.70	(2.13)
L)	Overhead	6.08	(2.76)
	TOTAL COST	47.92¢	(21.74¢)

TABLE 11

MANCHESTER WATER WORKS
REACTIVATION COSTS
JUNE 1980 THROUGH MARCH 1981
BASED ON REACTIVATION OF 842,401 KGS (1,857,176 LBS) OF GAC

COST ITEM	TOTAL COST	TOTAL UNITS	UNIT RATES
A) Makeup Carbon	$ 131,349.	96,876 kg (213,575 lbs)	$ 1.3558/kg ($0.615/lb)
B) Labor for Reactivation	36,029.	4,922 man-hours	7.32/hr
C) Labor for Transportation	5,200.	710.4 man-hours	7.32/hr
D) Labor for Lab	929.	122.9 man-hours	7.56/hr
E) Labor for Administration	24,515.	2,074 man-hours	11.82/hr
F) Parts and Service Calls	49,587.	N/A	N/A
G) Fuel Oil	41,415.	151 m^3 (40,015 gals)	274.27/m^3 (1.035/gal)
H) Electrical Power	9,286.	175,207 KWH	0.053/KWH
I) Water	13,743.	162,064 m^3 (42,813,084 gals)	0.848/m^3 (0.321/ 1,000 gals)
J) Lab Supplies	929.	N/A	N/A
K) Depreciation	39,587.	3,570 hours	47,505/yr for 10 mos.
L) Overhead	51,338.	N/A	77% of labor
TOTAL	$ 403,907.		

N/A = Not Applicable

TABLE 12

EXPLANATION OF REACTIVATION COST ITEMS FOR MANCHESTER, NH

A) Makeup Carbon. Based on an average total carbon loss of 11.5% experienced through 5 cycles of reactivation at a delivered cost to Manchester of $1.36/kg (61.5¢/lb).

B) Labor for Reactivation Operation and Maintenance. Based on a staff of 12 water treatment plant operators at an average wage of $7.32/hr. Each operator spent an average of 9.4 hours of a 42-hour workweek operating and maintaining the GAC reactivator.

C) Labor for Transport Operation and Maintenance. Based on a staff of 12 water treatment plant operators at an average wage of $7.32/hr. Each operator spent an average of 1.6 hours of a 42-hour workweek transporting GAC to and from the filter beds to the reactivator.

D) Labor for Laboratory Analysis to monitor quality control of the reactivation process. Based on a staff of 1 laboratory technician at a wage of $7.56/hr. This technician spent an average of 9.8 hours of a 35-hour workweek associated with GAC reactivation work.

E) Labor for Administration. Based on a staff of 2 engineers, chemist, secretary, purchasing agent and accountant. Each individual spent an average of 9.8 hours of a 35-hour workweek associated with GAC reactivation work.

F) Parts and Service Calls. Based on a total item cost of $49,587 for new parts, repair shop charges, and outside service calls. This work does not include MWW labor.

G) Fuel Oil. Based on an average cost of $0.273/l ($1.035/gal) of fuel oil, and consumption of 42.4 L/hr (11.2 gals/hr) of reactivation for 6,601 BTU/kg of GAC (2,994 BTU/lb of GAC).

H) Electrical Power. Based on an average cost of 5.32¢/KWH and a consumption of 48.6 KW/hr of operation for process and building energy, or 0.205 KWH/kg of GAC (0.093 KWH/lb).

I) Water. Based on water production cost of $.0848/$m^3$ ($0.321/1,000 gals) and a consumption of 44.64m^3/hr (11,792 gals/hr) of reactivator operation, or 0.189m^3/kg (22.7 gals/lb) of GAC. This includes water for both transport and reactivation. Approximately, 92% of the water is for reactivation and 8% used for transport.

Table 12 (Continued)

J) Lab Supplies to perform reactivation process quality control analysis. Based on a total item cost of $929.

K) Depreciation. Based on the straight line depreciation calculations shown in Table 13.

L) Overhead. Based on a MWW overhead factor of 77% above labor costs that include holidays, vacations, sick leave and fringe benefits. The total overhead for the overall MWW system is 305% and includes acquisition, treatment, distribution, and support services.

TABLE 13

MANCHESTER WATER WORKS
DEPRECIATION CALCULATIONS
(ITEM K of TABLE 11)

COST	TOTAL	EQUIPMENT	BUILDING
A) Construction (Table 8, items A and B)	$755,500	$528,600	$226,900
B) Other Capital (Table 8, items F,G,H, and I)	104,700	73,255	31,445
	$860,200	$601,855	$258,345

Straight Line Depreciation (based on time):

Equipment: Estimated useful life is 15 years.
Annual depreciation is $601,855/15 = $40,123.7/year.

Building: Estimated useful life is 35 years.
Annual depreciation is $258,345/35 = $ 7,381.3/year.

Total annual depreciation is $40,123.7 + $7,381.3 = $47,505/year.

Estimated Unit Depreciation Cost: (Applicable to regional reactivation)

It is assumed that the maximum effective use of the system is 75%* of the time during the year, 24 hrs/day.

Estimated maximum use = .75 x 365 x 24 = 6,570 reactivation hours/year

Unit depreciation cost = $47,505/6,570 = $7.23/hr of reactivation.

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*Assumption made for regional costing, not actual on-site.

SECTION 9

PHASE II: GAC MONITORING PROGRAM AND RESULTS

General

The objective of this evaluation was to determine the degree of treatment effectiveness and changes in physical properties of GAC over 3 reactivation cycles. Virgin GAC was placed in one-half of WTP test filter #1 and monitored over 3 separate reactivation exhaustion runs. The remaining half of the test filter contained 5-year old service carbon once reactivated at the start of the monitoring program. Each successive run compared the GAC's performance in the respective filter halves over 3 reactivation exhaustion cycles. A summary of the run numbers and associated study conditions for each reactivation exhaustion cycle is presented below.

Evaluation	Date Start to End	GAC Study Condition
Run 1	1-31-80 to 5-30-80	Virgin Carbon (VC) Vs. Once Reactivated Service Carbon (SC)
Run 2	8-28-80 to 12-19-80	Once Reactivated (VC) Vs. Twice Reactivated (SC)
Run 3	2-16-81 to 5-17-81	Twice Reactivated (VC) Vs. Three Times Reactivated (SC)

These tests were made under full-scale, side by side treatment conditions to ensure equivalent hydraulic loading, backwashing frequency and flow duration for each GAC condition studied. The GAC's adsorptive capacity for TOC, ITHM and THMFP, and its effect on color removal, turbidity removal, pH and bacteriological growth was also studied. Laboratory GAC analyses for iodine number, apparent density, sieve analysis, modified phenol value, surface area, pore size distribution and other test parameters were used in the study. Determination of losses incurred during transport and reactivation was treated as equal importance during the investigation.

In addition to the GAC test filter monitoring program, water quality measurements were also made in all other phases of the WTP process as shown in Table 14. The WTP process presented in this section can be compared to the performance data for GAC. While the GAC comparisons were emphasized, the WTP process

TABLE 14

MWW WATER QUALITY MONITORING PROGRAM

SAMPLE SITE NO.	SAMPLE LOCATION	TOTAL SAMPLES PER WEEK					
		ITHM	THMFP 3A, 3M	THMFP 7A, 7M	TOC	TURBIDITY & pH	TC & SPC
1.	Raw	1	1	1	2	7	1
2.	Pre Flash Mix	1	1	1	2	7	1
3.	Post Flocculation	(Sample Site Eliminated)					
4.	Post Sedimentation	1	1	1	2	7	1
5.	Post Sand Filtration	2	2	1	3	7	1
6.	Post GAC Test Filter	2	2	1	3	3	1
7.	Post GAC Test Filter	2	2	1	3	3	1
8.	Combined Plant Post GAC	1	1	1	2	7	1
9.	Typical Mid and End Distribution Sites	2	1	1	2	2	2

NOTE:
3A - THMFP for 3 days, Cl_2 contact at ambient temperature conditions
7A - THMFP for 7 days, Cl_2 contact at ambient temperature conditions
3M - THMFP for 3 days, Cl_2 contact at 28.50°C (maximum system temperature)
7M - THMFP for 7 days, Cl_2 contact at 28.50°C (maximum system temperature)

analyses provided a useful reference in assessing the significance of the GAC's adsorptive capacity.

Experimental Design

Comparisons of GAC treatment performance and physical property changes were conducted on a full-scale basis. The Manchester, NH Water Treatment Plant is a 152,000m^3/day (40 MGD) system equipped with 4 GAC filter beds of 38,000m^3/day (10 MGD) flow capacity each. The filter beds are a multicompartmented downflow design located after the sand filters and before the treatment plant clearwell (Figures 1 and 7). At average day flow of 49,400m^3/day (13.0 MGD), the EBCT for the 4 filters operating in parallel was 23.3 minutes. Table 15 provides a summary of the GAC filter-bed specifications.

TABLE 15

MANCHESTER WATER TREATMENT PLANT - GAC FILTER BED DATA

Item	Description	
Length	33.53 M	(110 ft)
Width	4.9 M	(16 ft)
Depth of Media	1.2 M	(4 ft)
EBCT (Avg.)	23.3 Minutes	
(Min.)	7.6 Minutes	
Surface Loading (Max.)	159L/Min/M^2	(4 gpm/ft^2)
Daily Capacity (Max.)	38,000 M^3	(10 MGD)
GAC Capacity	108,864 Kg	(241,920 lbs)
Number of Compartments	108	
GAC/Compartment	1,008 Kg	(2,240 lbs)
GAC Specification	Westvaco, WVW	
	Iodine Number	900 mg/g
	Decolorizing Index	4 DIU
	Apparent Density	.569 gm/cc (35 lbs/ft^3)
	Mesh Size	8 x 30

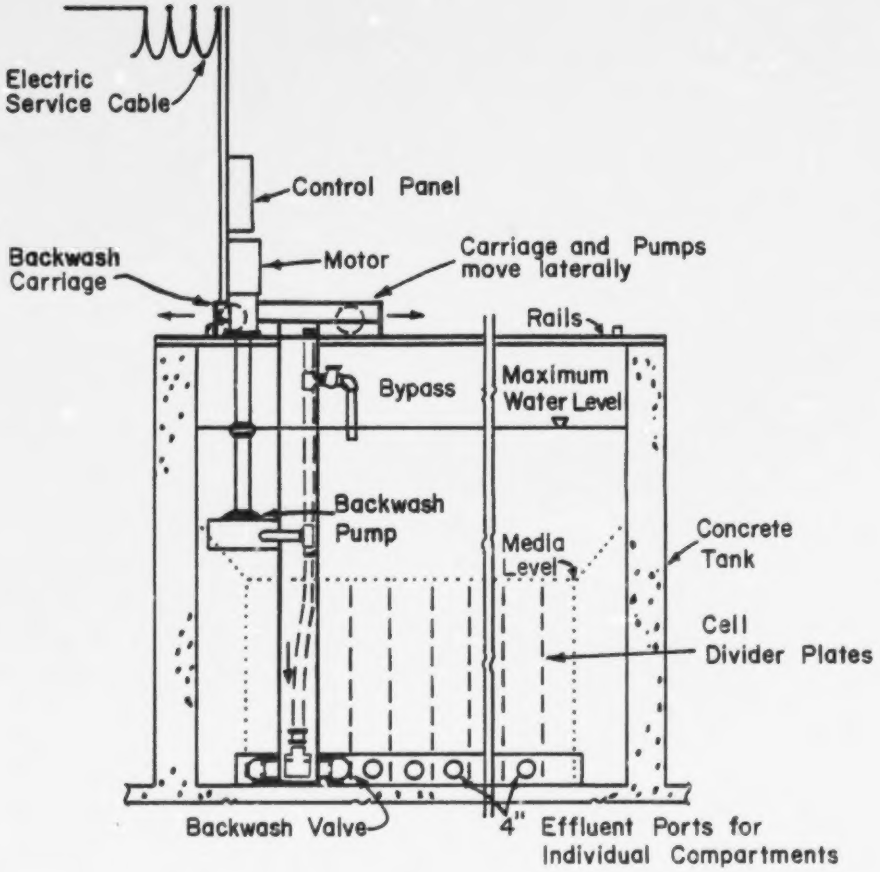

Electric
Service Cable
Control Panel
Backwash
Carriage
Motor
Carriage and Pumps
move laterally
Rails
Bypass
Maximum
Water Level
Backwash
Pump
Media
Level
Concrete
Tank
Cell
Divider Plates
Backwash Valve
4" Effluent Ports for
Individual Compartments

Figure 7 Sectional view — Automatic backwash GAC filter.

The compartmented design of these filter beds makes possible the segregation within a single filter bed of differing medias and effluents. Carbon filter #1, which was designated as the test filter, had one-half of its original 5-year old service carbon volume removed and replaced with a comparable grade of virgin carbon. In the remaining test filter half, the 5-year service carbon was removed, reactivated and replaced. By repeating this full-scale side by side comparison of GAC medias, the basic experimental conditions were established. Table 16 provides a tabulation of the actual GAC volumes and masses studied in each monitoring run. As indicated, overall fluctuation from run to run was less than 10% for these parameters. Through a data evaluation technique which compared the actual loading of the GAC on a mass basis, these variances were minimized further. Utilization of a single filter bed in this manner assured equivalent hydraulic loading, flow rate, backwash rate and run time on both halves of the filter bed. Effluent from the filter bed is collected in a rectangular channel (parallel to the filter) and flows vertically to a rectangular overflow weir along the entire length of the filter channel. Therefore, there is negligible lateral (horizontal) mixing in the filter bed effluent channel. This vertical upflow design ensures that samples collected on the bottom of the filter bed effluent channel will be free from interferences due to lateral mixing between filter ends.

Based on this flow pattern, an aqueous sampling system (Figure 8) was designed and installed in the filter bed effluent channel to provide discrete and representative sampling from each half of the filter bed. The sampling system consists of 2 independent manifolds, each collecting GAC effluent water through 3 intake risers located 3, 6, and 9 M (10.7, 21.4 and 32.1 ft) from the opposite ends of the GAC filter bed effluent channel. The central 15 M (49 ft) portion of the GAC filter effluent channel was not sampled. Because this portion of the test filter was not involved in either the aqueous or GAC property sampling programs, it received all makeup GAC required following reactivation.

The test filter sampling system was constructed of copper, brass and cast iron with teflon tape used at all threaded joints. Based on recommendations for minimizing sampling system interferences, all soldered joints were washed with acetone before installation. The entire system was then operated continuously for well over 2 weeks at a flushing rate of approximately 40L (10.6 GPM) before test filter sampling of effluent quality was begun. A comparison of water samples taken concurrently from the new sampling system and directly from the filter effluent channel proved to be identical for all parameters studied. All other WTP aqueous samples were taken from the existing WTP sample water system (Figure 9). This system runs continuously and has been in service nearly 7 years at the start of the test filter monitoring program. These sampling systems were also checked against grab samples and found to be identical.

TABLE 16

SUMMARY OF GAC INVENTORIES*

Runs	Test Filter Bed North (Site 6)	Test Filter Bed South (Site 7)
Run #1		
Volume, M^3 (ft^3)	98 (3,364)	97.1 (3,333)
Apparent Density, gm/cc (lb/ft^3)	.61 (38.1)	
Weight of GAC, Kg (lb)	54,780 (120,751)	56,330 (124,168)
Daily Avg. Flow, M^3/Day (MGD)	7,230 (1.91)	7,230 (1.91)
Run #2		
Volume, M^3 (ft^3)	95 (3,261)	100 (3,433)
Apparent Density, gm/cc (lb/ft^3)	.56 (34.9)	.58 (36.2)
Weight of GAC, Kg (lb)	53,200 (117,268)	58,650 (129,282)
Daily Avg. Flow, M^3/Day (MGD)	11,130 (2.94)	11,130 (2.94)
Run #3		
Volume, M^3 (ft^3)	93 (3,193)	96 (3,296)
Apparent Density, gm/cc (lb/ft^3)	.57 (35.6)	.57 (35.6)
Weight of GAC, Kg (lb)	53,010 (116,850)	54,460 (120,046)
Daily Avg. Flow, M^3/Day (MGD)	7,270 (1.92)	7,280 (1.92)

*1. All values shown are from MWW measurements.

2. Reference Table 16, site #6 refers to half of the GAC test filter initially filled with virgin GAC.

3. Reference Table 16, site #7 refers to half of the GAC test filter with one-time reactivated GAC.

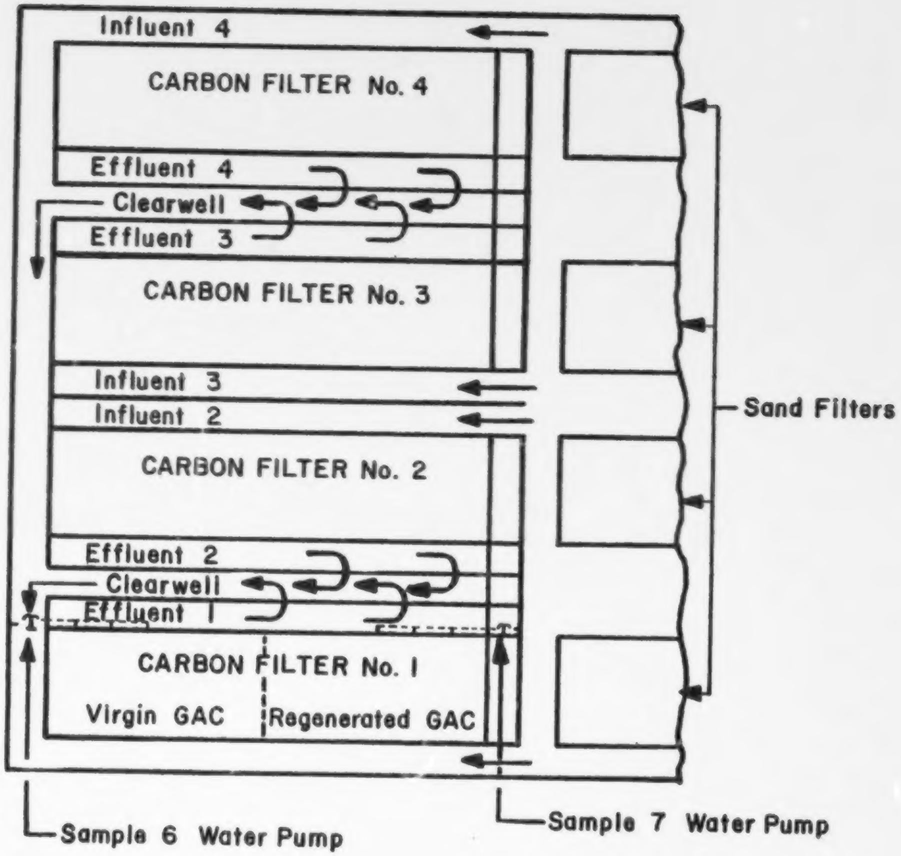

Influent 4
CARBON FILTER No. 4
Effluent 4
Clearwell
Effluent 3
CARBON FILTER No. 3
Influent 3
Influent 2
CARBON FILTER No. 2
Effluent 2
Clearwell
Effluent 1
CARBON FILTER No. 1
Virgin GAC
Regenerated GAC
Sand Filters
Sample 6 Water Pump
Sample 7 Water Pump

Figure 8. GAC Filter Configuration — Manchester, N.H. Water Treatment Plant.

Full-scale, side by side evaluations were completed for 3 monitoring cycles. The length of each filter run was at least 90 days in duration with cycle termination determined by test filter performance for ITHM and TOC removal. The criteria established for determining cycle termination was ITHM breakthrough, i.e., $C_e = C_i$, and TOC steady state, i.e., $C_e = kC_i$. Details of the aqueous monitoring program are indicated in Table 14.

Test filter flows were calculated on a daily basis as indicated below. While these calculations represent an indirect means of determining actual flow, there was no feasible method for obtaining direct flow measurements without major structural revisions to the filter.

$$\text{Test Filter Flow, } (M^3/\text{Day})^* = Q \times \frac{TFT}{CCT}$$

Q = WTP daily production (M^3/Day)
TFT = Test filter operating hours (Hrs/Day)
CCT = Total combined operating hours (Hrs/Day)

*This equation gives total filter bed flow in M^3/day. Each filter half was assumed to process one-half of this total.

Lab personnel at the MWW laboratory performed the complete aqueous sampling and analysis program for water quality. TOC was measured by the use of a Dohrmann DC-54 low level analyzer. ITHM and THMFP analyses were performed on a Perkin-Elmer Sigma I gas chromatograph utilizing liquid/liquid extraction with methylcyclohexane solvent. The integrating capacity and excellent support locally available for the GC system at Manchester was the major criteria involved in its selection.

A high level of quality control (QC) was stressed during these analyses. Performance samples from the Environmental Monitoring and Support Laboratory (EMSL) of EPA were analyzed quarterly and additional check samples were run inhouse. The QC program undertaken at Manchester is summarized in Table 17.

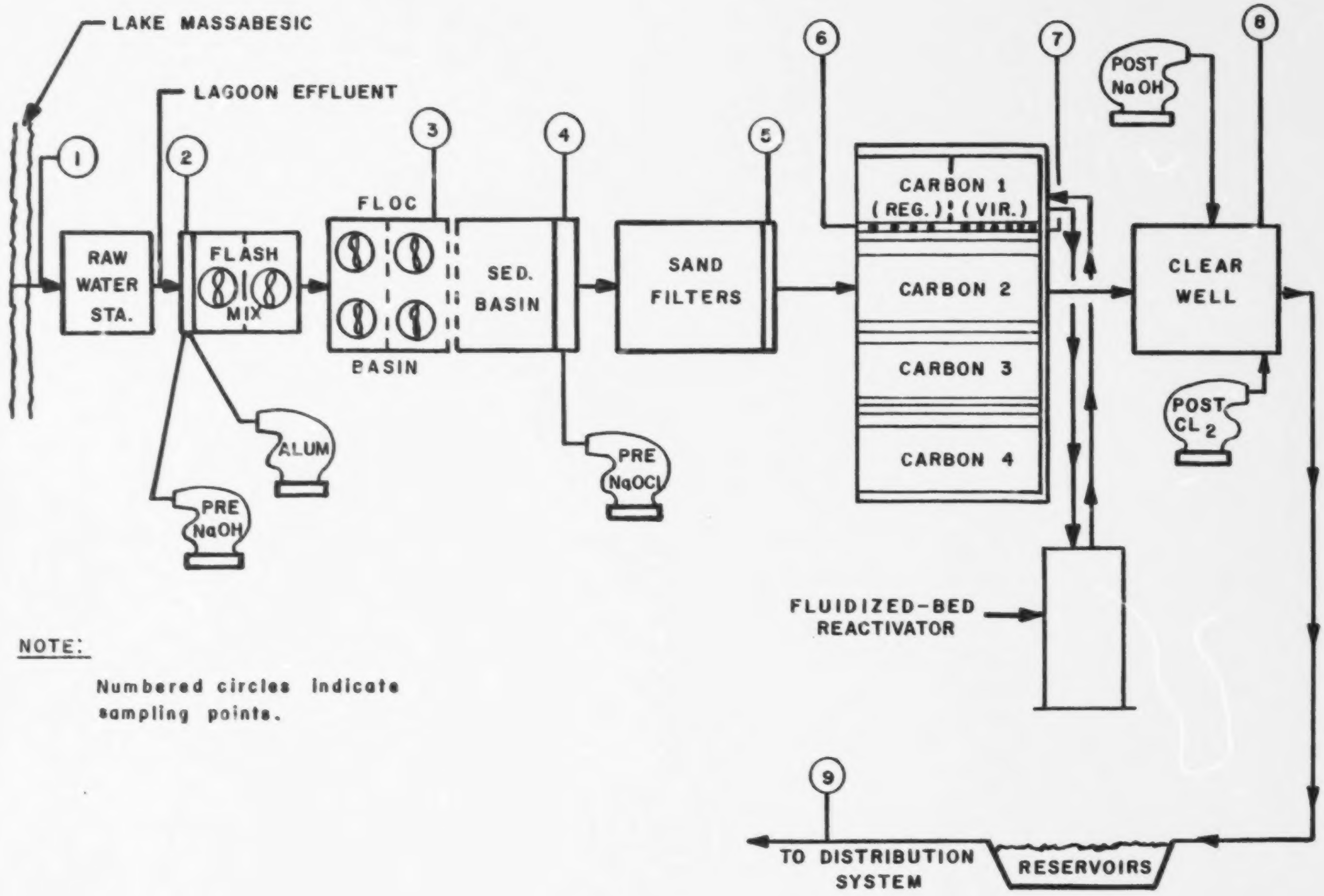
The MWW lab also analyzed the GAC routinely for IN, DI, AD, SA, MPD and AN. These laboratory analyses were provided both for QC in the reactivation and in fulfillment of other grant requirements. In a similar area, loss analyses were developed and performed on a routine basis to assist in compiling data on the reactivation and associated GAC transport system.

Outside analyses were solicited for reactivator exhaust gas evaluation and for further GAC laboratory analyses. The latter testing area was provided by Stanton B. Smith, Ph. D., a consultant in Carbon Technology, Doraville, GA and by the Georgia

TABLE 17

QUALITY CONTROL SCHEDULE SUMMARY

Analysis	Quality Control Measure	Frequency/Week
Trihalomethanes (THM)	Solvent Blanks	5
	Detector Check	5
	Raw Water Blanks	5
	Area/Baseline Sensitivities	1
	EMSL Check Samples	1 set/quarter
	External Standarizations	1
Trihalomethane Formation Potential	Terminal Free Chlorine Residuals and pH Measurements	4
Total Organic Carbon (TOC)	Electronics Check	6
	Machine Timing/Function	2
	System Blanks/Background Correction	6
	External Standards Check	1/month
	EMSL Check Samples	1 set/quarter
Turbidity	Standardizations	7
pH	Standardizations	7
Bacteriological	Buffered Water and Positives Run as per Standard Methods, Check Samples as Required	6
Apparent Color	Curve Standardization	1/month
Iodine Number Decolorizing Index	Standard GAC Analyzed with Each Batch of Unknowns. Duplicates Run with Outside Laboratory	1 set/batch
Free Chlorine Residual	DPD and Amperiometric Procedures Checked Against Each	1/month


LAKE MASSABESIC
LAGOON EFFLUENT
①
②
③
④
⑤
⑥
⑦
⑧
⑨
RAW WATER STA.
FLASH MIX
FLOC BASIN
SED. BASIN
SAND FILTERS
CARBON 1 (REG.) (VIR.)
CARBON 2
CARBON 3
CARBON 4
CLEAR WELL
POST NaOH
POST CL 2
ALUM
PRE NaOH
PRE NaOCl
FLUIDIZED-BED REACTIVATOR
RESERVOIRS
TO DISTRIBUTION SYSTEM

NOTE:

Numbered circles indicate sampling points.

Figure 9. Sampling and chemical feed location schematic.

Tech. Experiment Station, Atlanta, GA. The stack analyses work was conducted by Environmental Research and Technology Co. (ERT), Concord, MA.

The outside GAC lab work was performed at an interval coinciding with the exhaustion and reactivation of the test filter bed. Data including BET and PSD was gathered on the spent and reactivated GAC before and after reactivation, respectively. The outside GAC consultant also provided insight regarding these analyses which Manchester was not equipped to provide. The sampling of GAC for these analyses was very specific in location and timing. For run #1 only, samples were taken from the test filter bed prior to the test filter being placed in service. For runs #2 and #3, samples were also taken at the reactivator prior to and immediately after reactivation vessel. By broadening the scope of this sampling scheme, conclusions regarding the effect of transport versus the specific effects of reactivation were made possible. In each case of sampling being collected, whether from the test filter bed or from the reactivator, composites were drawn from numerous grab samples. The grab samples were collected in a methodical fashion at approximately 3, 6, and 9 M (10.7, 71.4 and 32.1 ft) from the ends of the test filter bed. These compartments correspond to the area where the intake manifolds were located in the effluent channel for aqueous analyses. Likewise, composites made at the reactivator were timed so as to intercept GAC entering the reactivation vessel from the same approximate area of the test filter bed (3, 6, and 9 M from the filter ends).

Water Quality Findings

Results of the water quality monitoring program are illustrated by the graphical presentations herein and tabular data (Appendix D). Three basic types of graphical presentations were developed. The first demonstrates concentration versus time, or breakthrough characteristics within the test filter and depicts the daily variations in water quality at the WTP. The second graphic presentation displays percent removal verus time. This presentation was found to be particularly useful in determining when a steady-state condition was achieved in the test filter and in comparing WTP unit processes for their relative effectiveness in reducing TOC, ITHM and THMFP concentrations. The third type of graph depicts the adsorbate loading on the GAC. This graph was considered useful in comparing the data from one test filter to another. It should be noted, however, that differences in ambient temperature and variations in average daily flow rate have to be taken into account in drawing any conclusions from the run to run comparisons.

The interrun comparisons were performed in spite of these differences for a number of reasons. The first concerns the basic question: Do subsequent, repeated reactivations cause GAC to lose or gain adsorptive capacity? Perhaps, the most important aspect of this question was whether it was valid to compare 2 different "batches" of GAC and assume that the adsorptive capacity would be equivalent. The virgin GAC purchased for this evaluation was produced in 1979 while the service GAC was produced in 1974 and first reactivated in 1979. While the specification and grade of the GAC was equivalent, the question remains that if substantial differences in performance were detected, could these differences be attributed to this one factor alone? If so, this argument then nullifies the validity of the side by side comparison in the test filter. In order to address this argument, graphical presentations of the loading characteristics of each batch of GAC in identical reactivation state have been prepared on a parameter by parameter basis (Figure 10 - 21). While some variances between the curves is evident, the curves generally show similar characteristics. It must be recognized that in drawing comparisons such as this, all the variables of differing temperature, EBCT as well as nature and concentration of influent TOC are apparent.

Further evidence of the similarity between the 2 batches of GAC involved is seen by the physical carbon analyses presented in Tables 19 and 20 as well as the pore size distribution analyses presented graphically in Figures 108 and 109. The combination of this data and the aqueous data substantiate the statement that the 2 batches of GAC do, indeed, exhibit similar characteristics.

WTP Water Quality Data Discussion

Instantaneous Trihalomethane Concentration (ITHM)

As indicated by Figures 22, 23 and 24, ITHM concentrations at the Manchester WTP are practically non-existent before the discharge point of the sedimentation basis. As indicated by Figure 9, this is the first point of chlorination in the water treatment process at Manchester. Increases in ITHM concentration from the sedimentation basin effluent to the GAC influent channel were clearly evident as the result of extended reactivation time for the production of THMs. A trend towards improved performance of the GAC filters (including the test filters) from the period of run #1 through run #3 for ITHM removal is clearly evident. Whereas in run #1 the average removal effectiveness of the GAC beds is seen to fluctuate widely (0 - 50%) without any clear pattern, by run #3 the GAC beds are consistently removing approximately 50% of applied ITHM, lowering the influent concentration from 12 ug/l to an effluent concentration of 6 ug/l on the average. This improvement in performance of the GAC service filters from 1979 to 1981 is a direct result of the reactivation of these units over this period. At the start of monitoring run #1, the WTP contained only one GAC filter bed

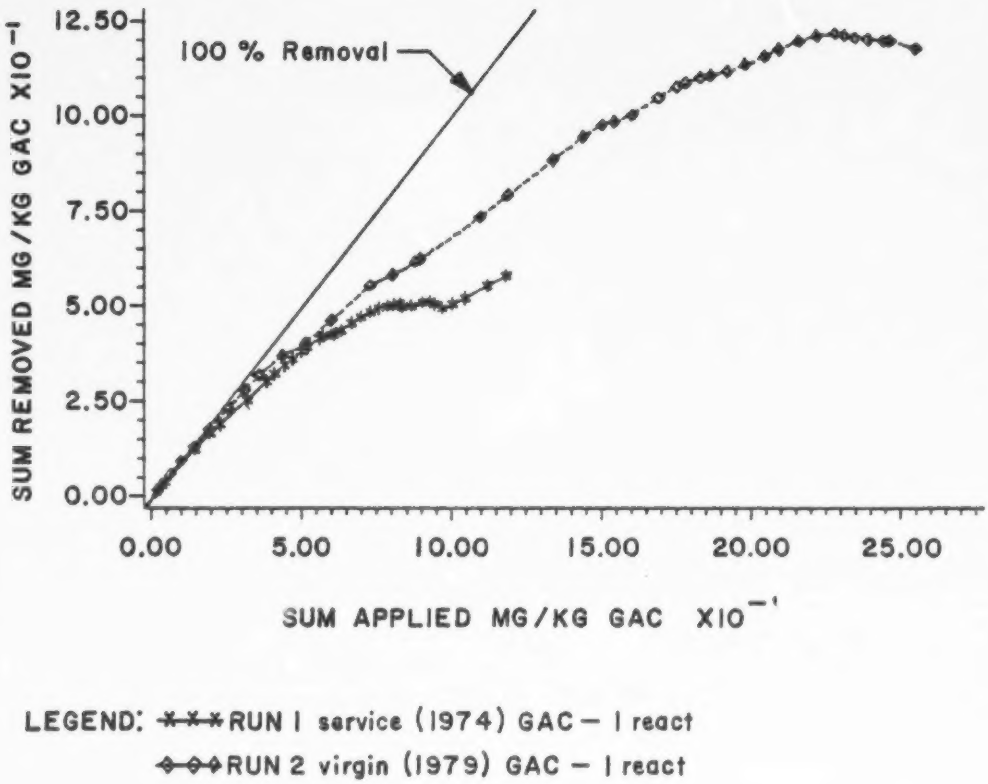


Figure 10. Comparison of GAC lots at one reactivation for ITHM removal.

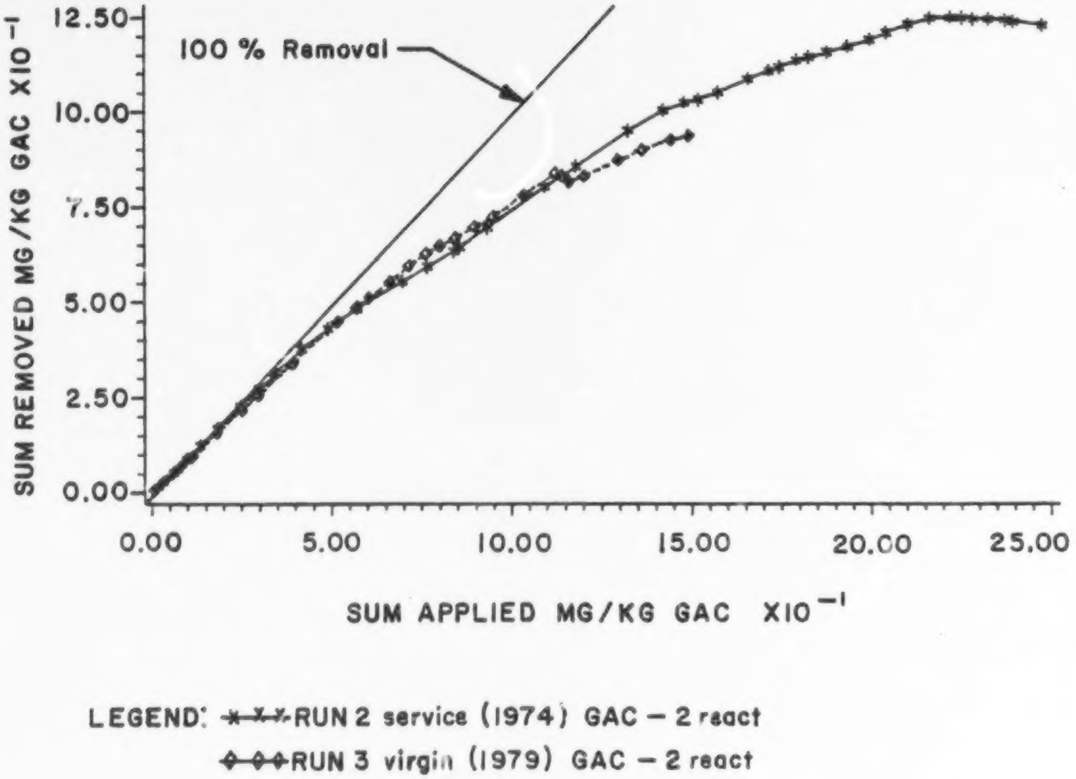


Figure 11. Comparison of GAC lots at two reactivation for ITHM removal.

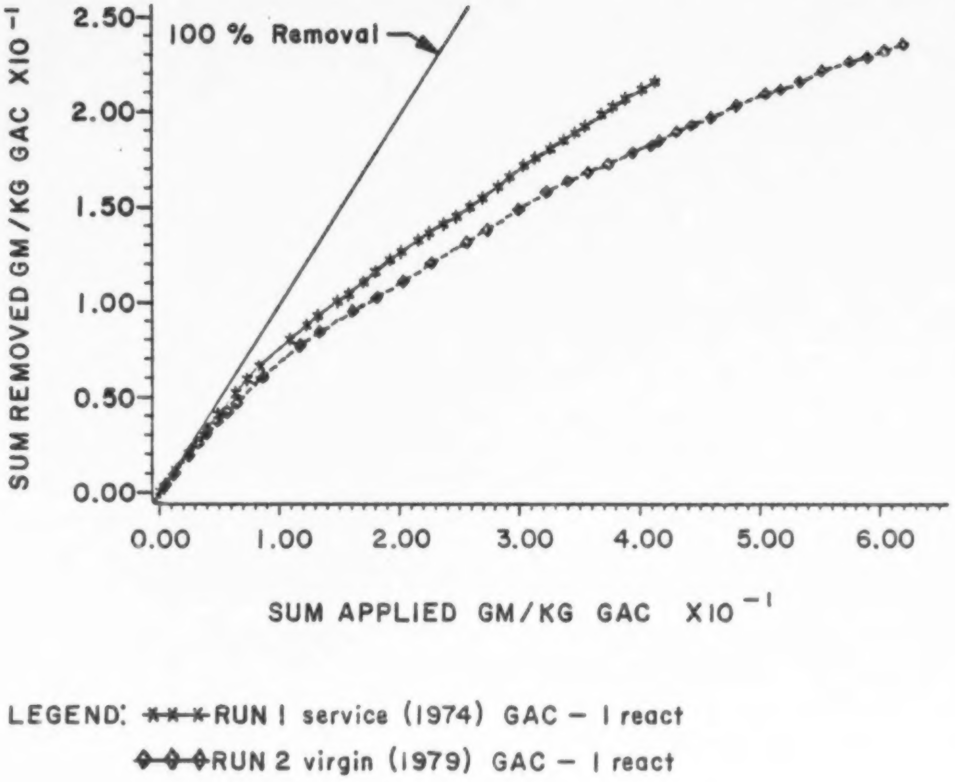


Figure 12. Comparison of GAC lots at one reactivation for TOC removal.

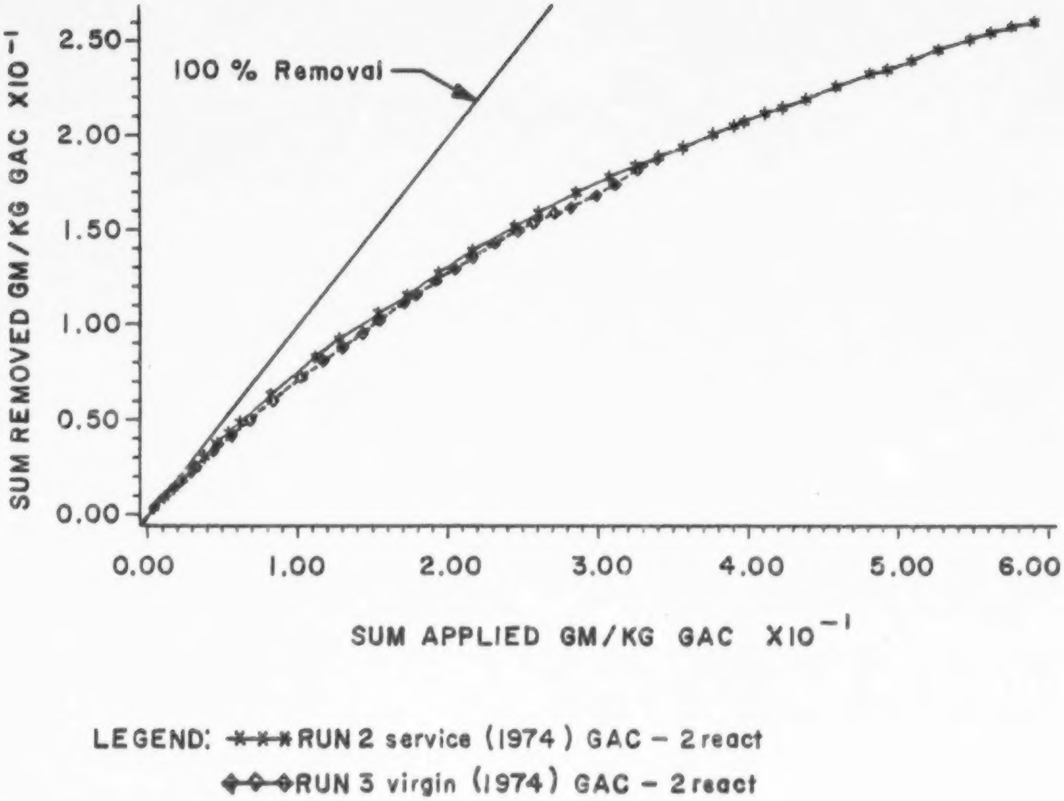


Figure 13. Comparison of GAC lots at two reactivation for TOC removal.

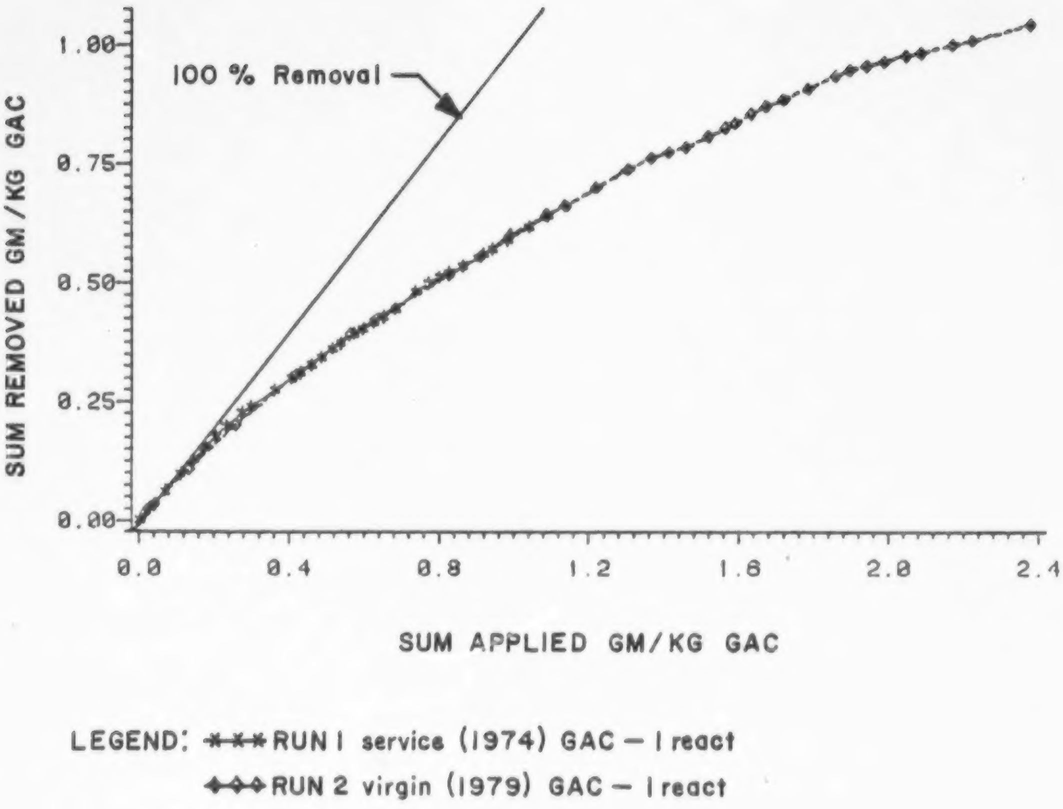


Figure 14. Comparison of GAC Lots at One Reactivation For 3 Day Amb. Temp. THMFP Removal.

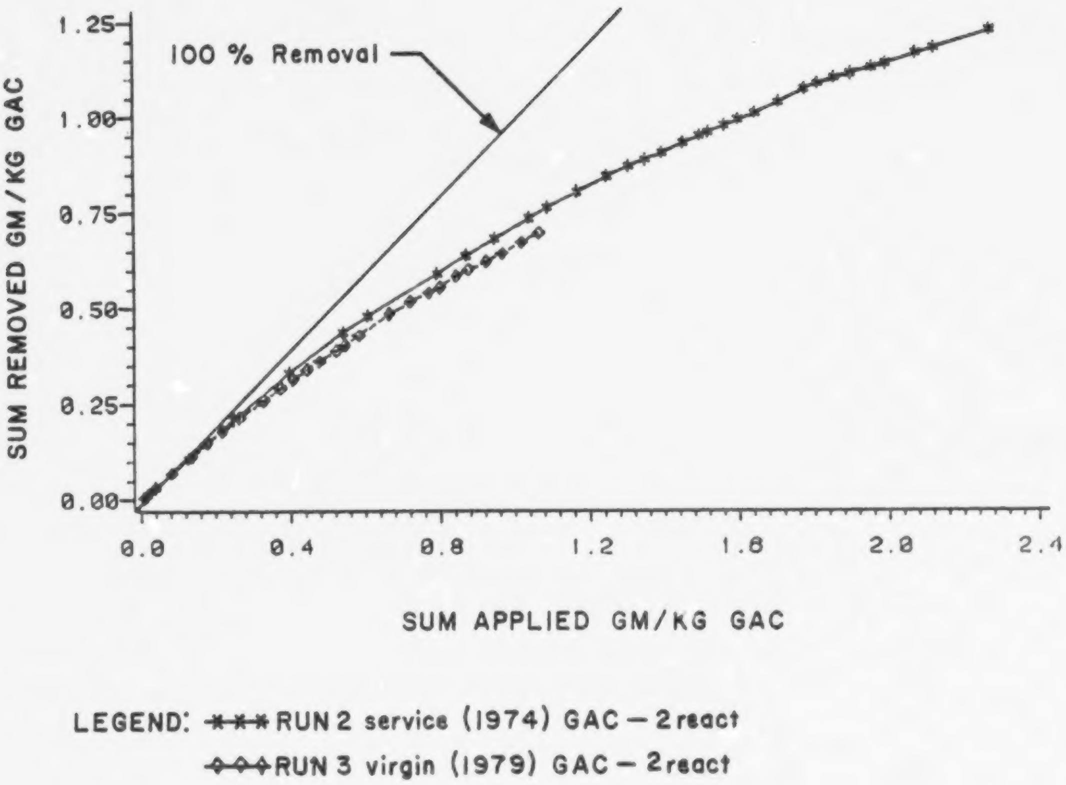


Figure 15. Comparison of GAC Lots at Two Reactivation For 3 Day Amb. Temp. THMFP Removal.

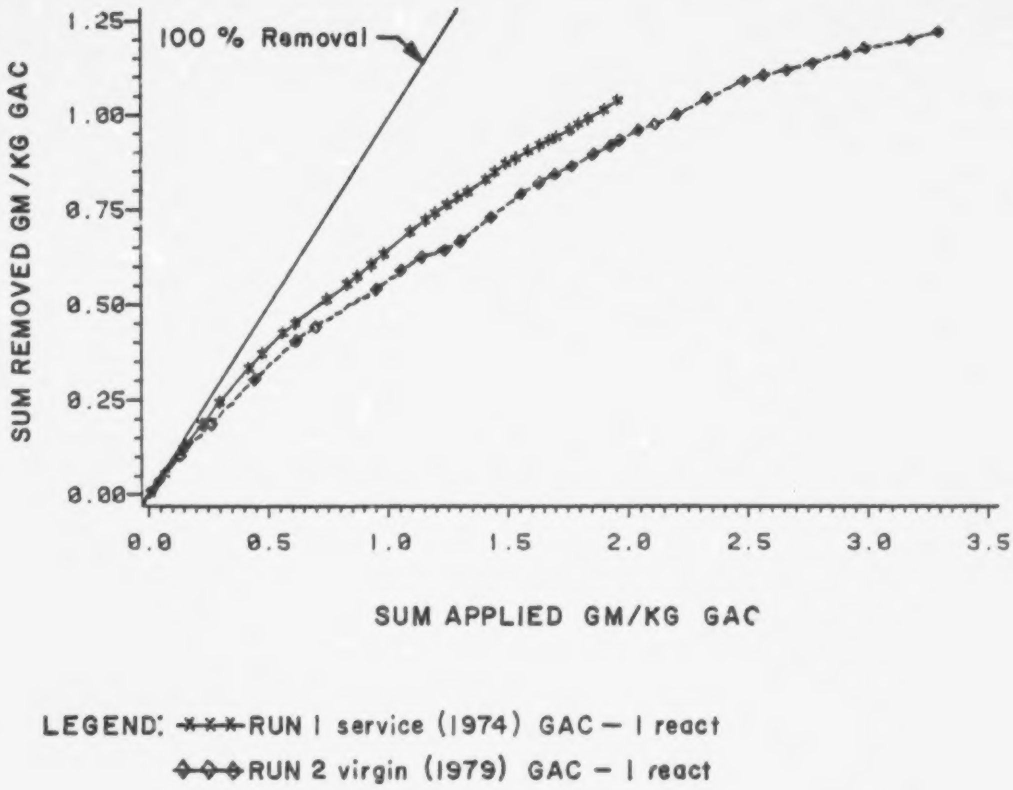
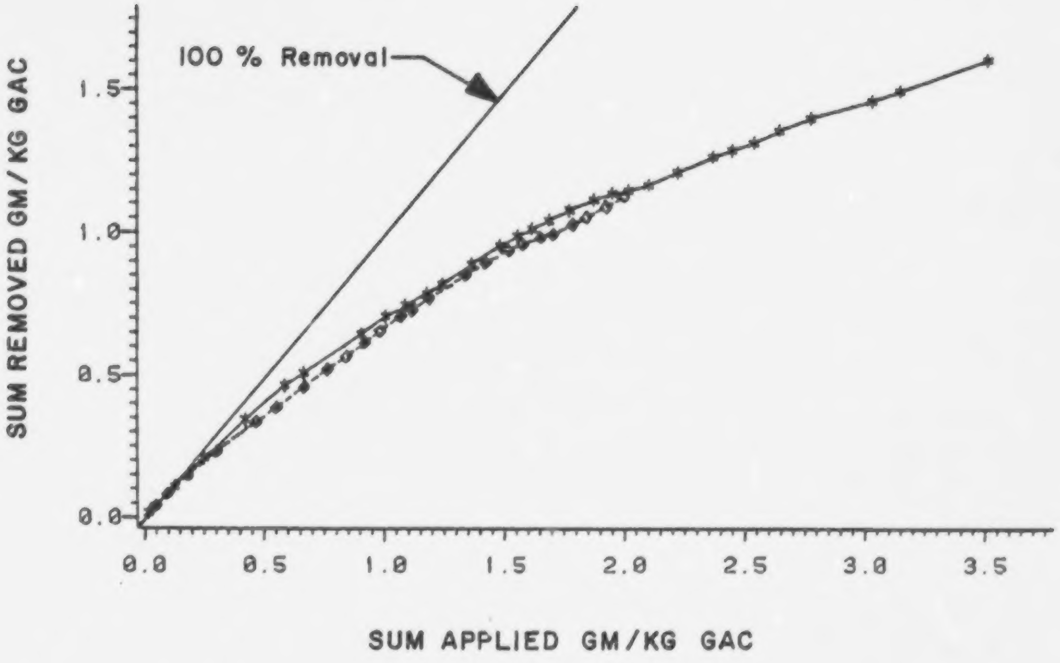


Figure 16. Comparison of GAC Lots at One Reactivation For 3 Day Max. Temp. THMFP Removal.



LEGEND: ✳✳✳ RUN 2 service (1974) GAC — 2 react
◇◇◇ RUN 3 virgin (1979) GAC — 2 react

Figure 17. Comparison of GAC Lots at Two Reactivation For 3 Day Max. Temp. THMFP Removal.

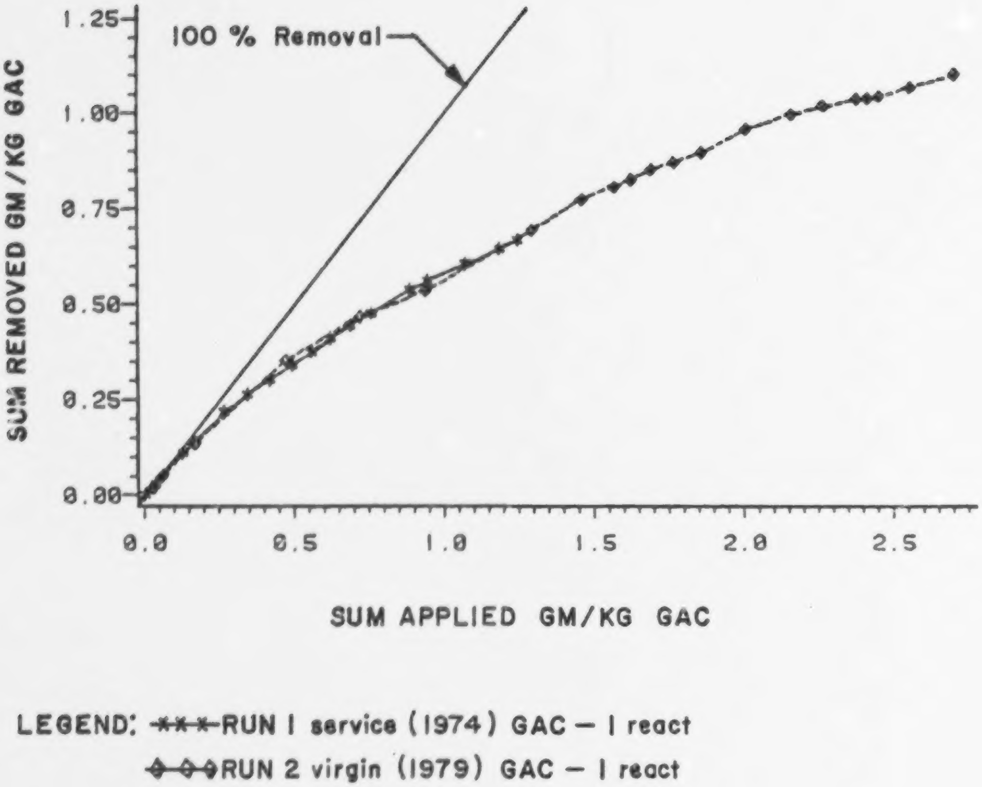


Figure 18. Comparison of GAC Lots at One Reactivation For 7 Day Amb. Temp. THMFP Removal.

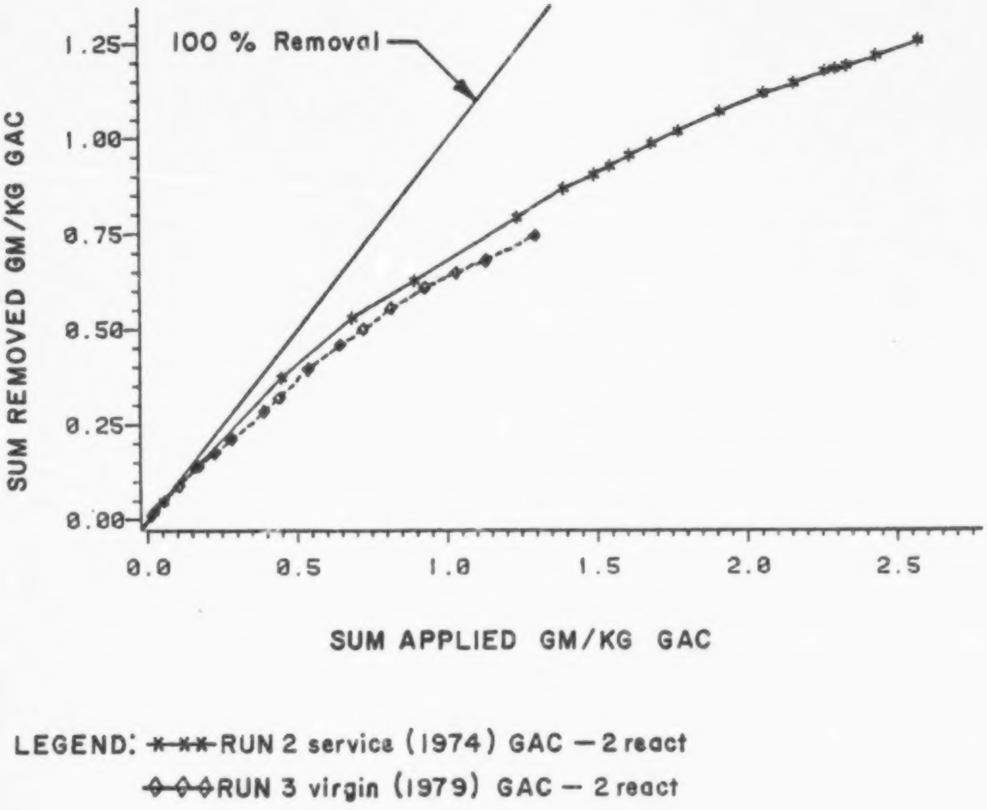


Figure 19. Comparison of GAC Lots at Two Reactivation For 7 Day Amb. Temp. THMFP Removal.

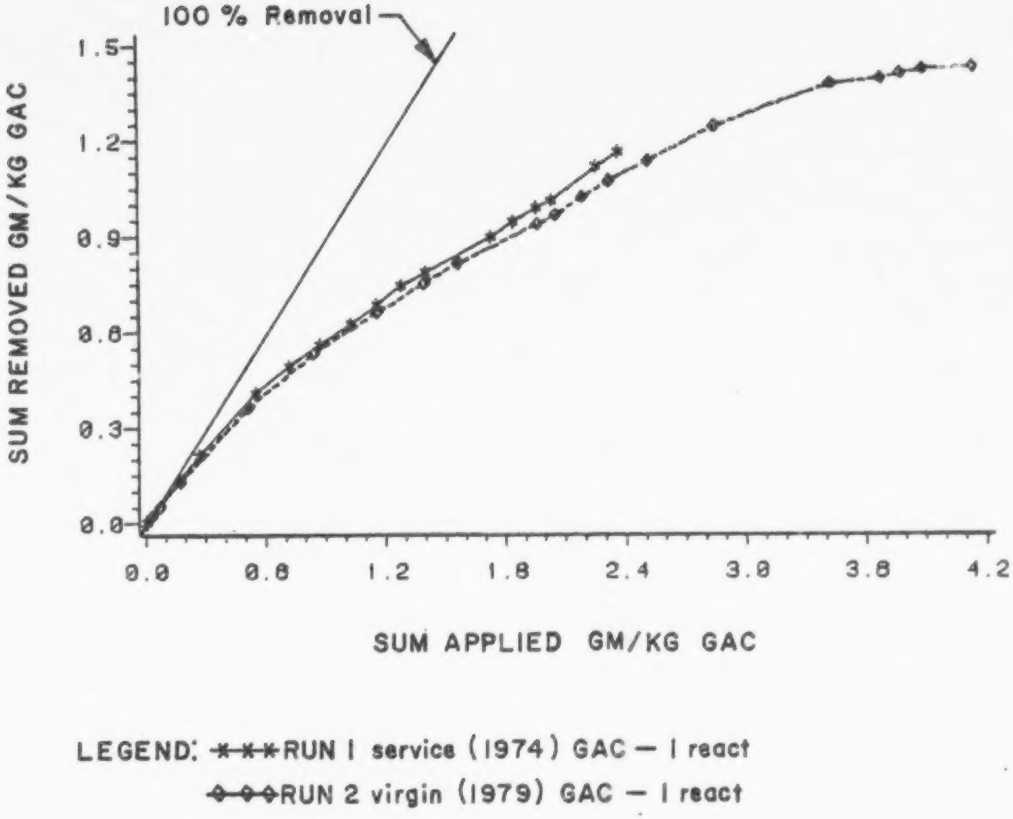


Figure 20. Comparison of GAC Lots at One Reactivation For 7 Day Max. Temp. THMFP Removal.

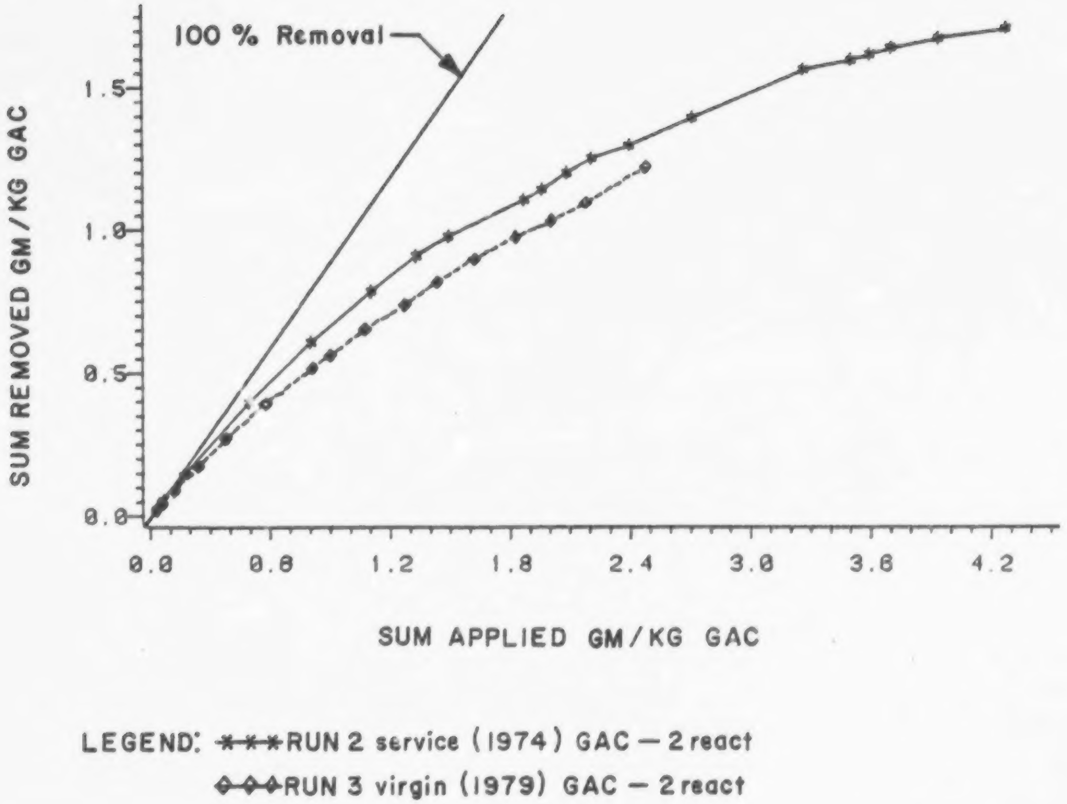


Figure 21. Comparison of GAC Lots at Two Reactivation For 7 Day Max. Temp. THMFP Removal.

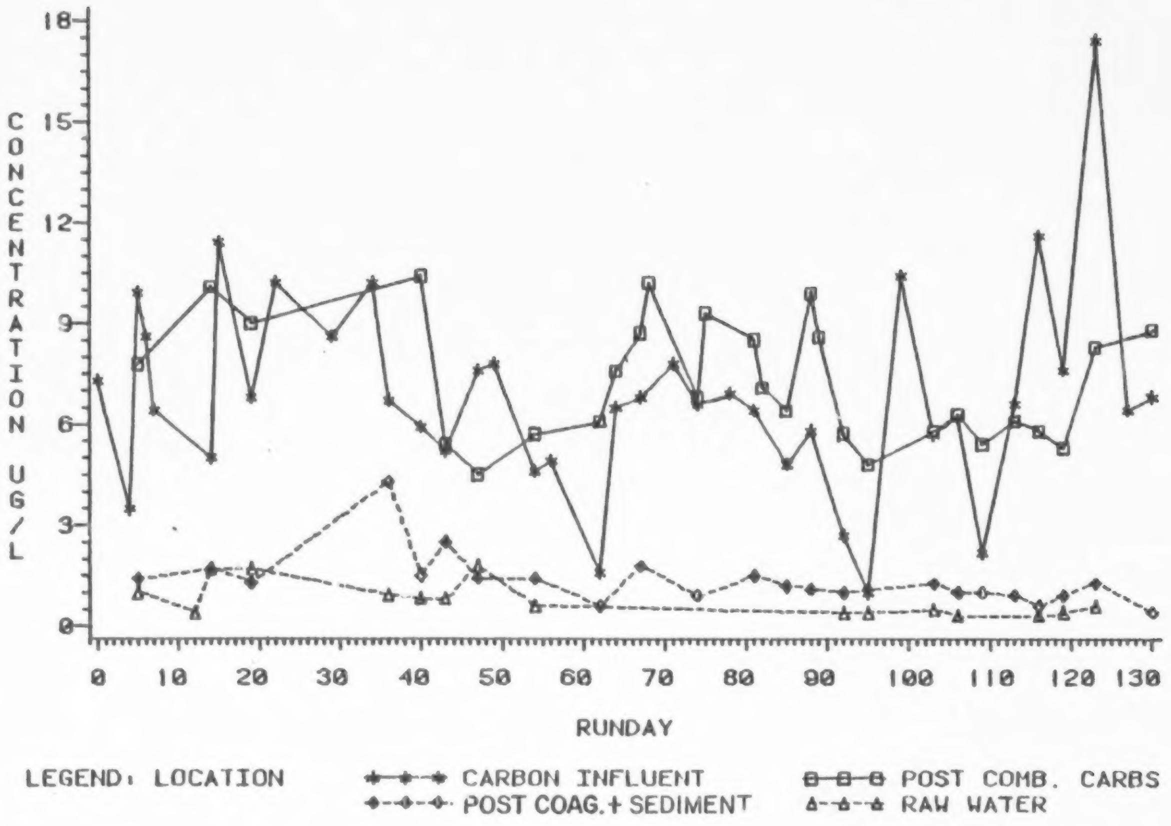


Figure 22. Run I.— WTP instantaneous trihalomethane concentrations.

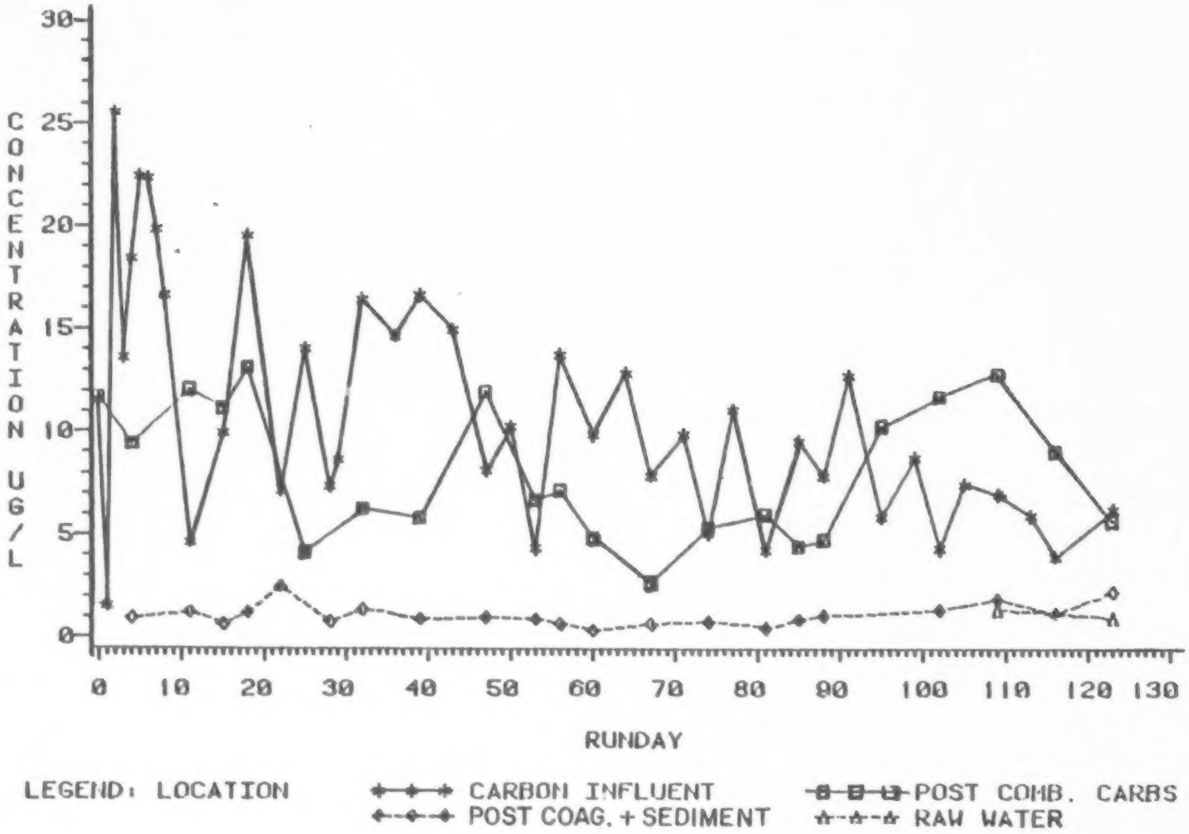


Figure 23. Run 2.—WTP Instantaneous trihalomethane concentrations.

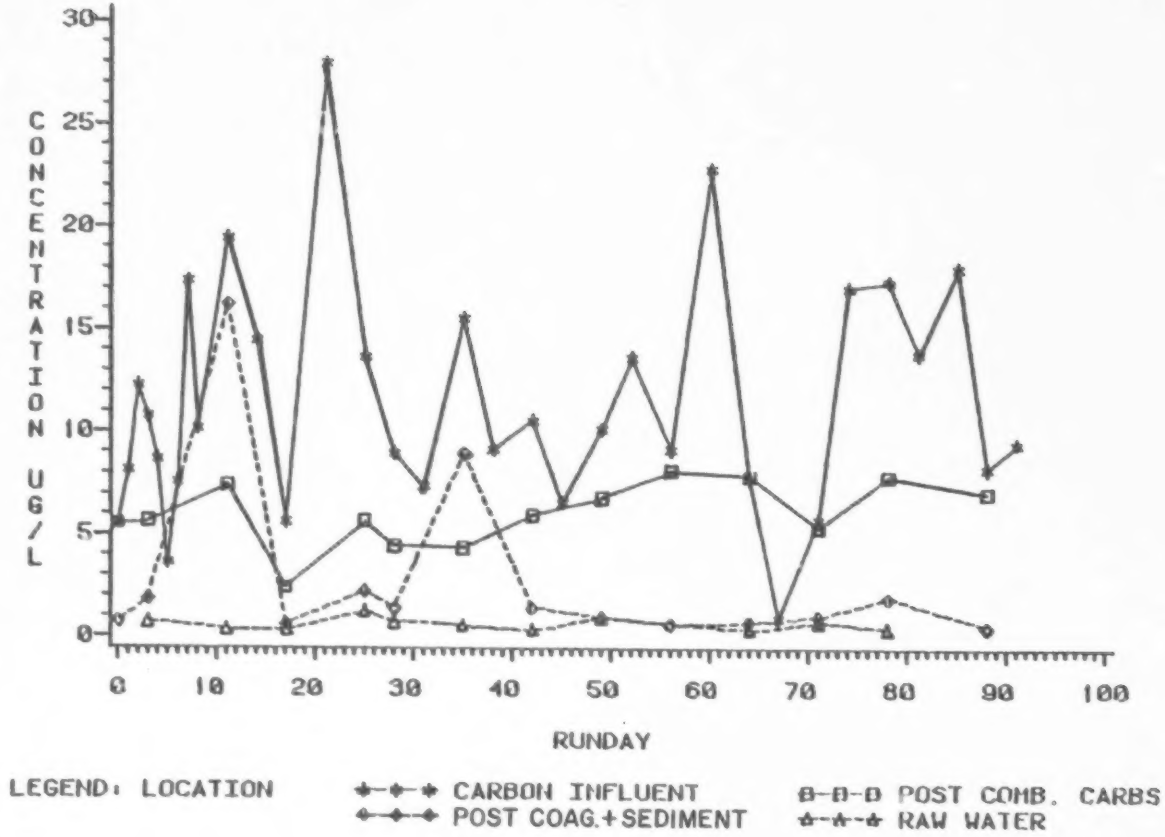


Figure 24. Run 3.— WTP instantaneous trihalomethane concentrations.

in a state of relative freshness, i.e., the "test" filter bed. Throughout the course of the project the reactivation unit was operated with GAC from the remaining filter beds. As each filter was reactivated and put into service, a noticable improvement in the clearwell water quality was seen. This trend towards improved performance of the GAC filtration system was witnessed for TOC and THMFP. Table 18 provides a summary of overall WTP performance for removal of ITHM, TOC and THMFP from run #1 to run #3.

Total Organic Carbon (TOC)/
Trihalomethane Formation Potential (THMFP)

TOC and THMFP concentrations, unlike ITHM, demonstrated a marked response to conventional treatment processes. Typical examples are seen in Figures 25 and 26, where the WTP performance for TOC and THMFP (7 day, 28.5°C) reduction during run #2 is indicated. The WTP unit process of aluminum sulphate coagulation and sedimentation followed by sand filtration is capable of lowering TOC and THMFP levels on the order of 35%. Further treatment by GAC filtration lowers the concentrations of these 2 parameters by an additional 42% (Table 18).

In addition to the 7-day, 28.5°C THMFP analysis, concurrent THMFP analyses were performed for 3 days at 28.5°C, 7 days at ambient water temperatures, and 3 days at ambient water temperatures. The relative concentrations encountered in each of these 4 THMFP reactions are typified by Figures 27, 28 and 29 which indicate the relative concentrations encountered in run #2 for the test filter influent and effluents. The largest THMFP values generally encountered were those seen in the 7-day analyses. It was thought that this reaction time represented the worst case condition for Manchester's distribution system. The 3-day THMFP analyses were selected due to the fact that this retention time was generally felt to represent the average situation for the MWW system. The decision to analyze for THMFP at 2 temperatures, 28.5°C and ambient, was reached based upon the desire to have a controlled THMFP analysis for interrun comparisons (28.5°C THMFP) and THMFP analysis for direct comparison to observed distribution system ITHM values (ambient °C THMFP). While the 3 and 7-day, 28.5°C constant temperature THMFP analyses provided an excellent run to run comparison of worst case THMFP conditions, the ambient temperature THMFP analyses was not representative of actual conditions within the distribution system. The relatively low level of free chlorine residual in the MWW distribution system as compared to that in the THMFP analysis produced ambient THMFP values approximately 2 to 4 times the values actually seen. As a result, the ambient THMFP analyses were not typical of full-scale system conditions. They are also not useful in a run to run comparison except coincidentally in runs #1 and #3.

TABLE 18

AVERAGE WTP PERCENT REMOVALS FOR ITHM, TOC, AND THMFP

Phase Treatment	Run #1			Run #2			Run #3		
	A	B	C	A	B	C	A	B	C
ITHM	-	-	13	-	-	27			42
TOC	33	19	32	23	12	46	-	13	48
3-day, 28°C THMFP	43	25	25	29	19	50	42	9	56
7-day, 28°C THMFP	38	12	33	24	10	42	30	13	50

Note: "A" - Removal via coagulation and sedimentation
"B" - Removal via sand filtration
"C" - Removal via combined GAC filtration

The TTHM concentrations seen in the THMFP analyses follow the pattern predicted by the thermodynamics of the reaction. Elevated temperature and contact time were shown to increase the terminal concentration of THM's. This consideration predicts that the colder water temperature should result in a lower average ambient THMFP than actually observed. The constant temperature (28.5°C) THMFP analyses varied primarily as a function of TOC concentration. This is demonstrated by Figures 25 and 26 of run #2 and Figures 30 and 31 of run #1. Figures 25 and 26 have a "Y" intercept for raw water TOC and THMFP of 4.15 mg/l and 225 ug/l, respectively. The ratio THMFP/TOC is 6.39×10^{-2}. In run #1 (Figures 30 and 31), this ratio is 6.42×10^{-2}. Run #3 was not included in this evaluation since the raw water TOC data is not sufficient to project a "Y" intercept as was the case in runs #1 and #2.

While it is recognized that the nature and concentation of the TOC constituents evaluated here vary from run to run, the preceding THMFP/TOC ratios are presented solely for the purpose of indicating the apparent relationship between the 2 parameters. There is no basis for expecting that this relationship would hold outside the MWW system, or even within the MWW system at some future date.

TOC concentrations ranged from 4 to 5 mg/l through the 3 monitoring runs. Additional TOC and THMFP data gathered over the 3 runs is presented in Figures 32 to 42.

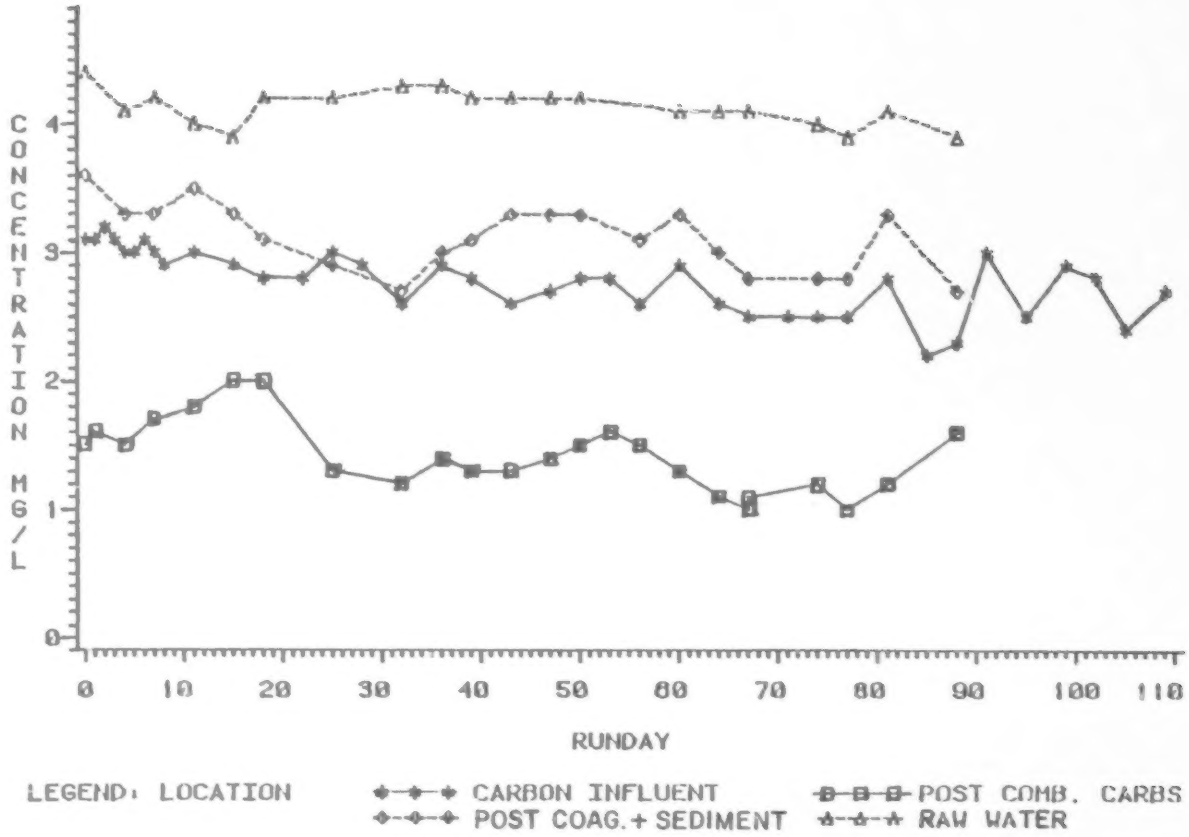


Figure 25. Run 2.— WTP total organic carbon concentrations.

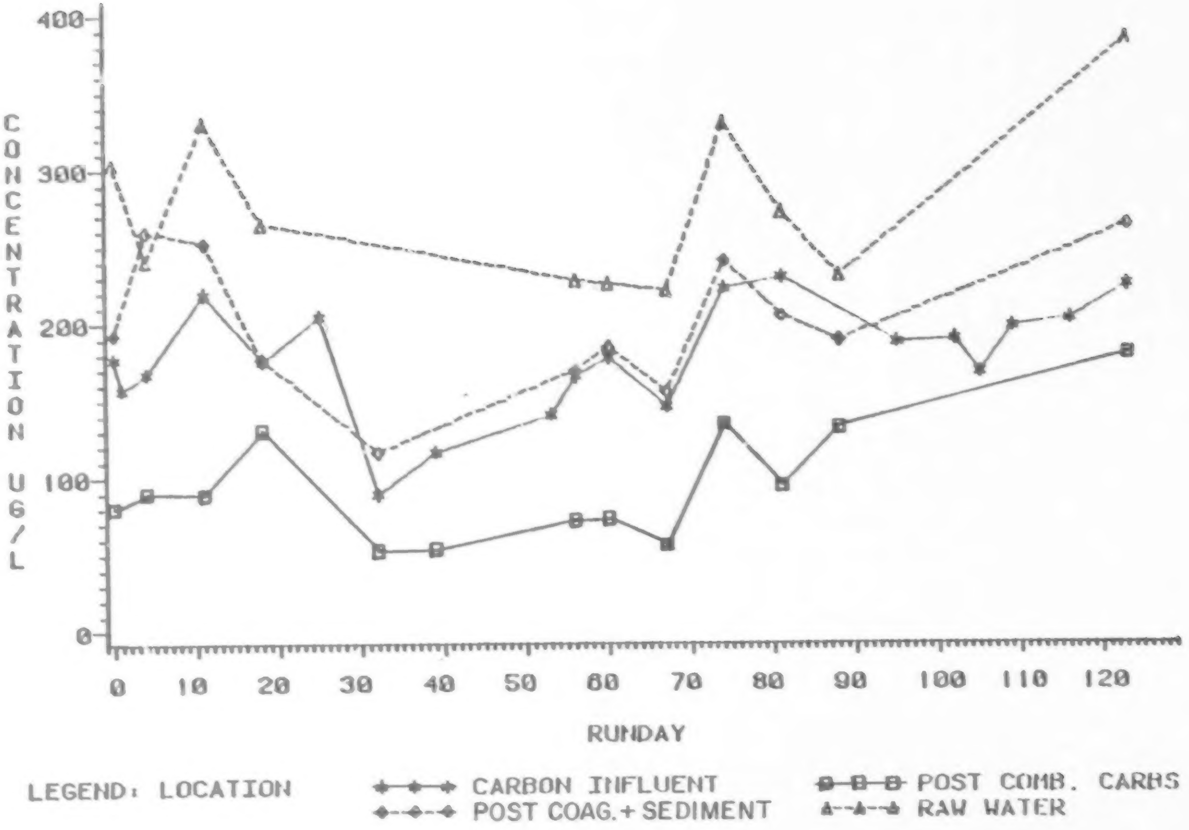
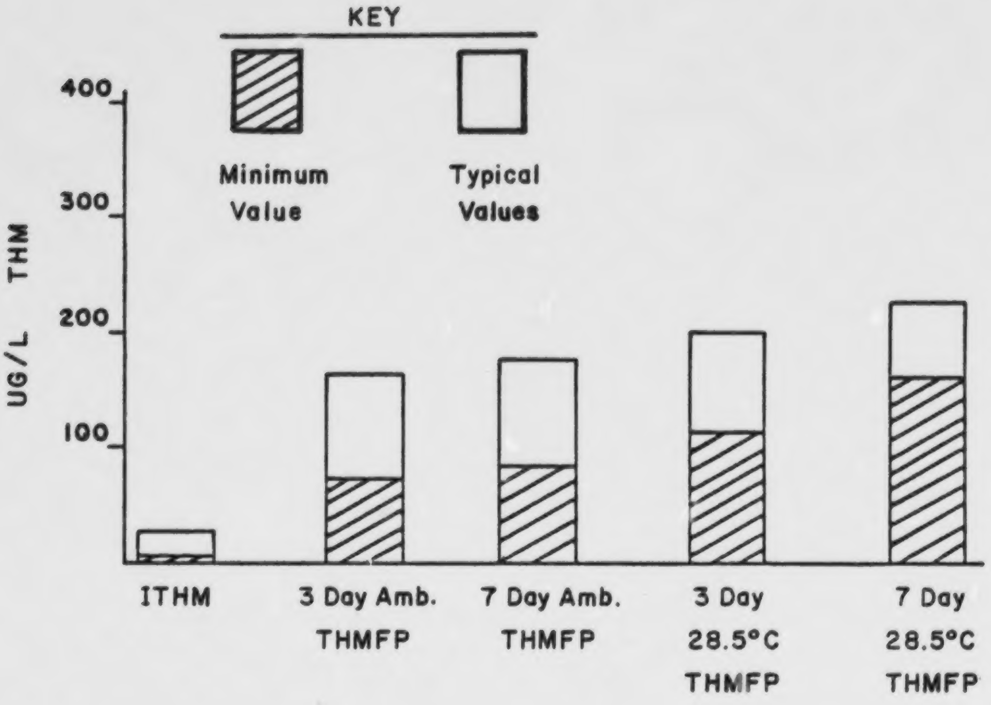


Figure 26. Run 2 — WTP seven day 28.5°C THMFP concentrations.

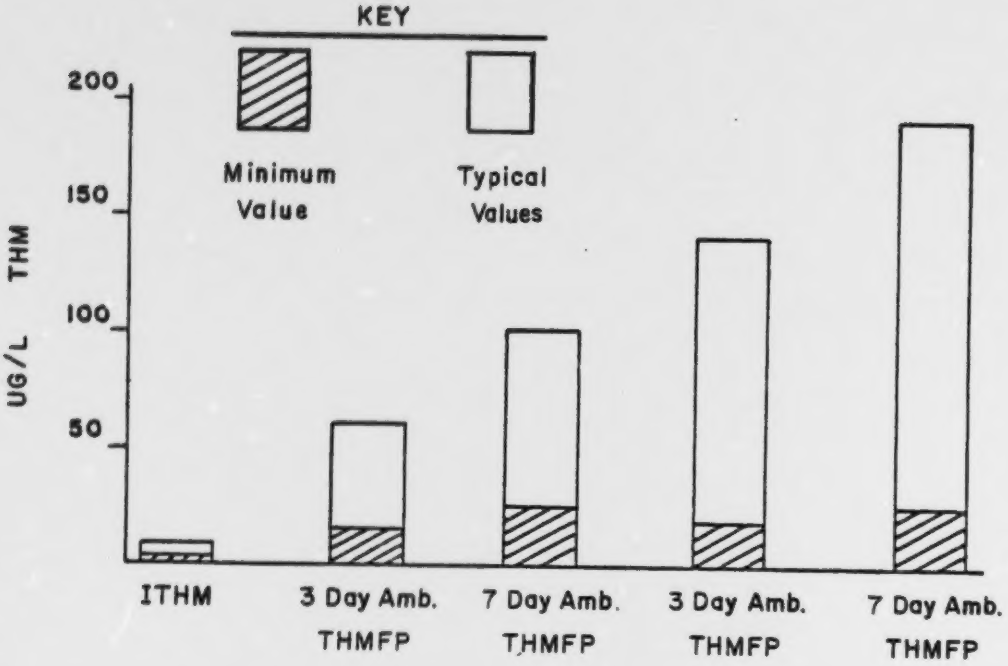


ITHM — Instantaneous Trihalomethanes

Amb. — Ambient Temperature

THMFP — Trihalomethane Formation Potential

Figure 27. Run 2.— GAC common influent concentrations to GAC filters for ITHM and THMFP.

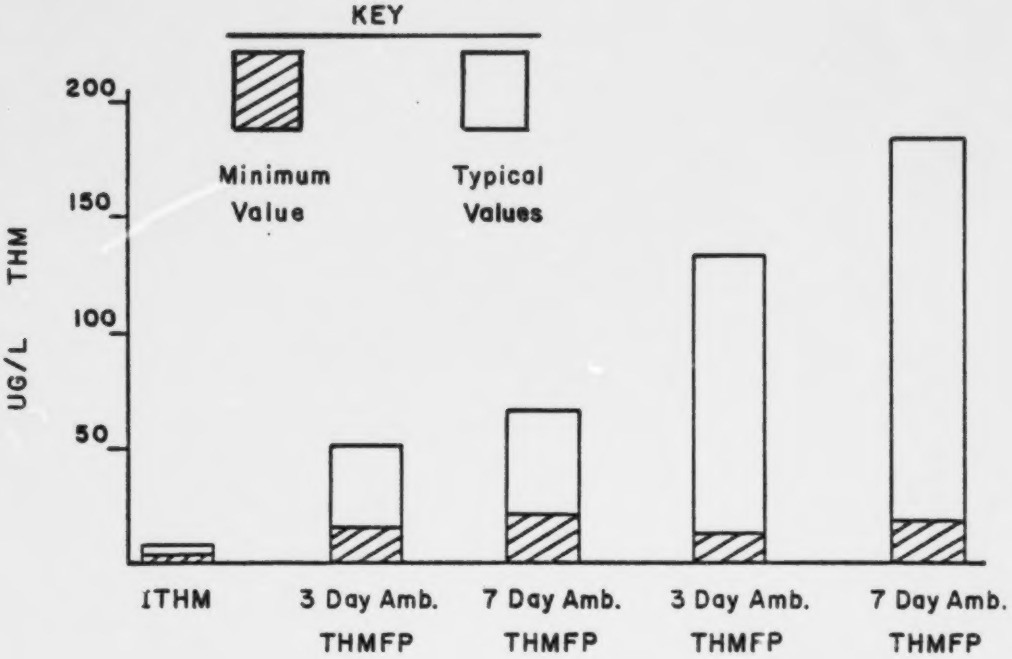


ITHM — Instantaneous Trihalomethanes

Amb. — Ambient Temperature

THMFP — Trihalomethane Formation Potential

Figure 28. Run 2.— Typical effluent concentrations of once reactivated (1979) GAC for ITHM and THMFP.



ITHM — Instantaneous Trihalomethanes

Amb. — Ambient Temperature

THMFP — Trihalomethane Formation Potential

Figure 29. Run 2.— Typical effluent concentrations of twice reactivated (1974) GAC for ITHM and THMFP.

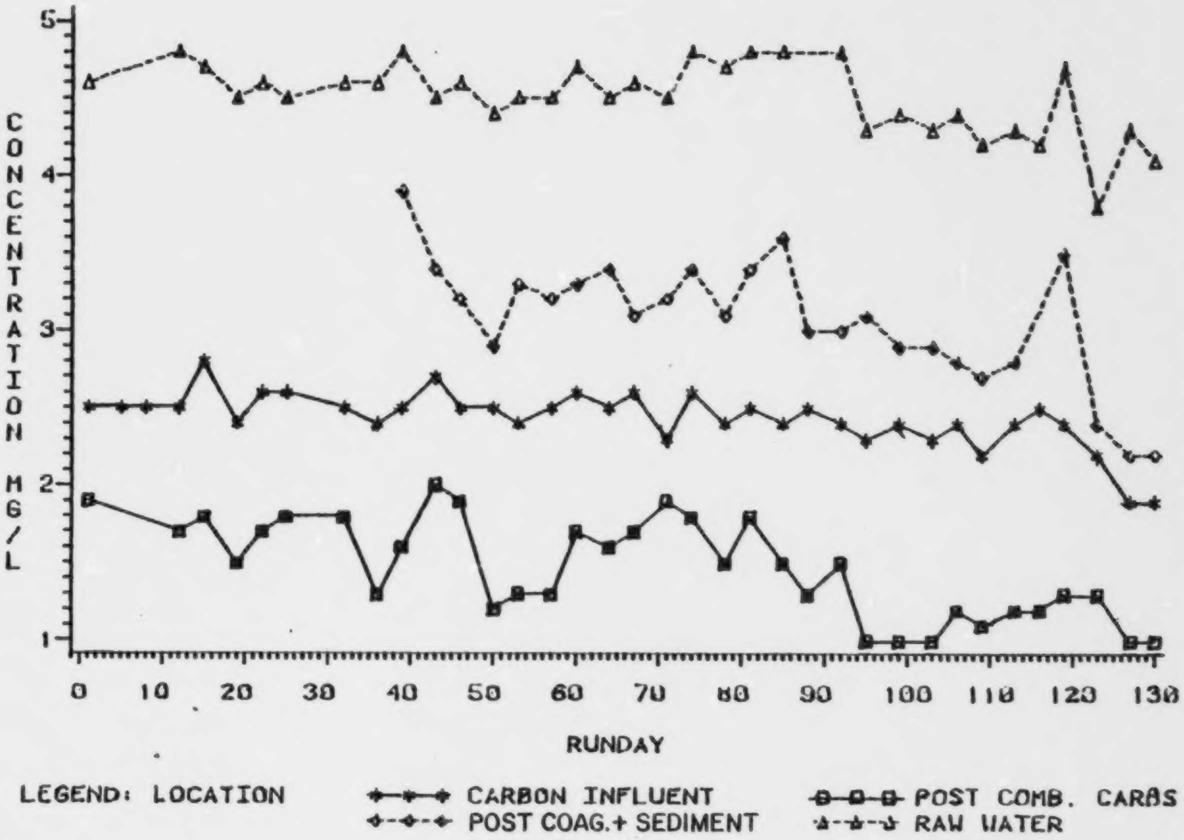


Figure 30. Run I.— WTP total organic carbon concentrations.

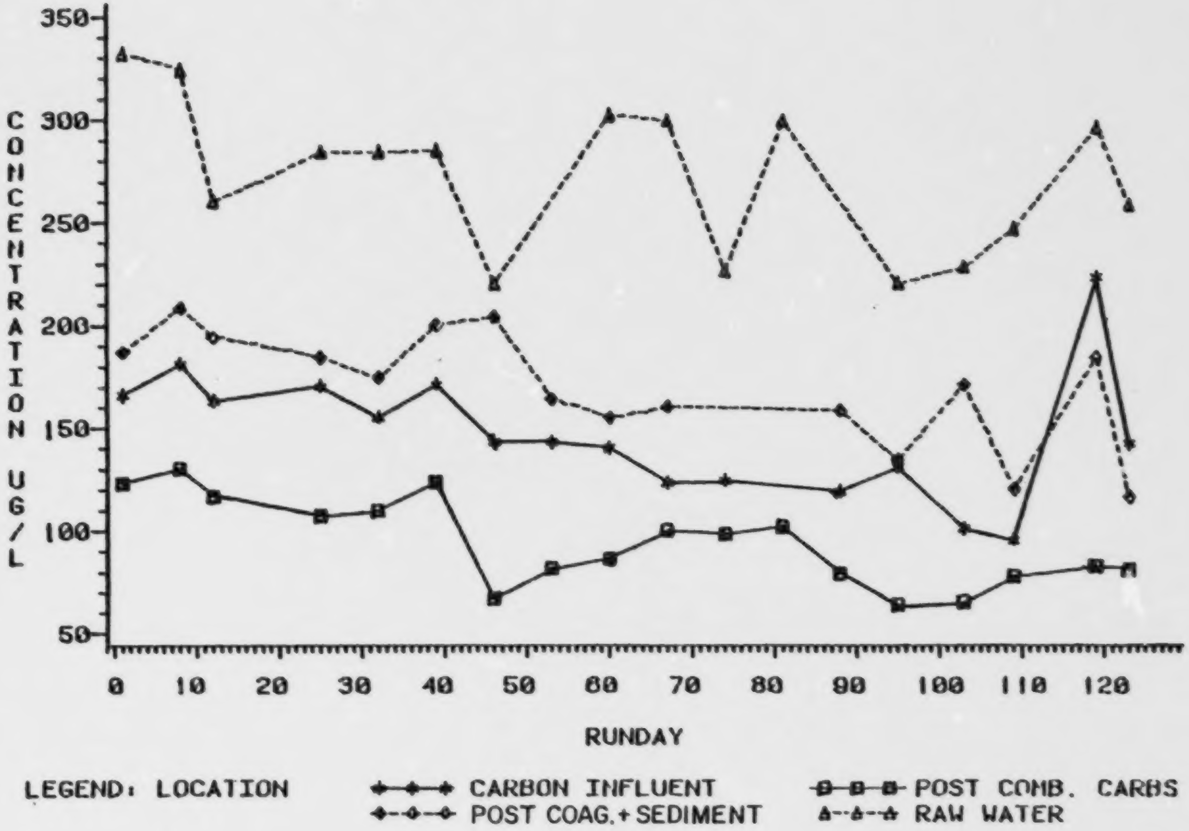


Figure 31. Run I. — WTP seven day 28.5°C THMFP concentrations.

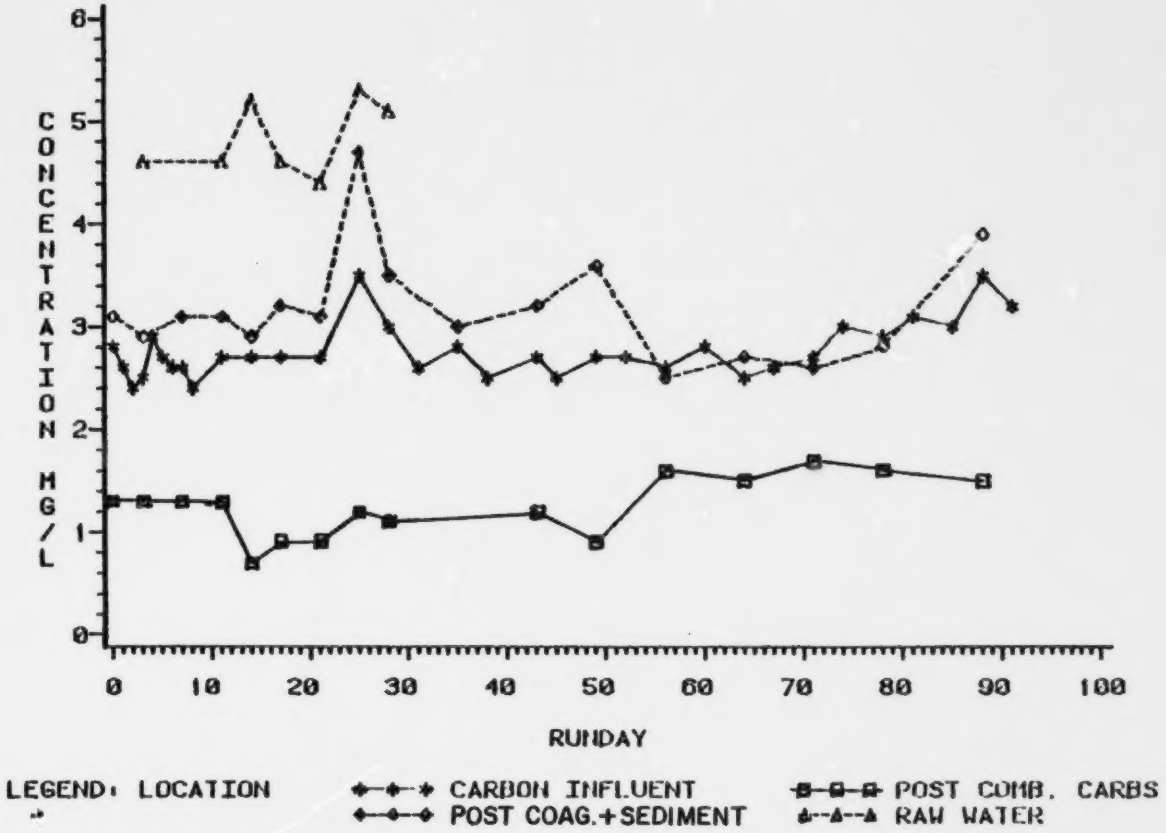


Figure 32. Run 3.— WTP total organic carbon concentrations.

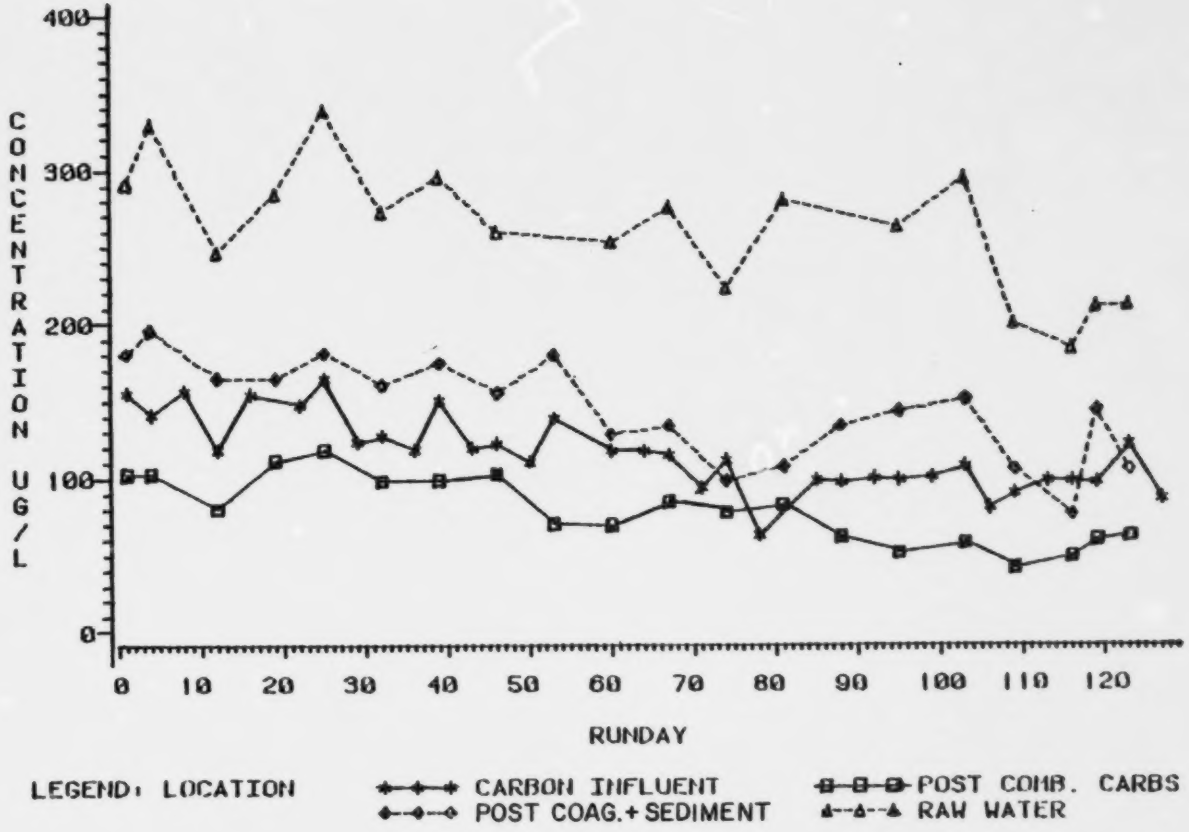


Figure 33. Run I.— WTP three day 28.5°C THMFP concentrations.

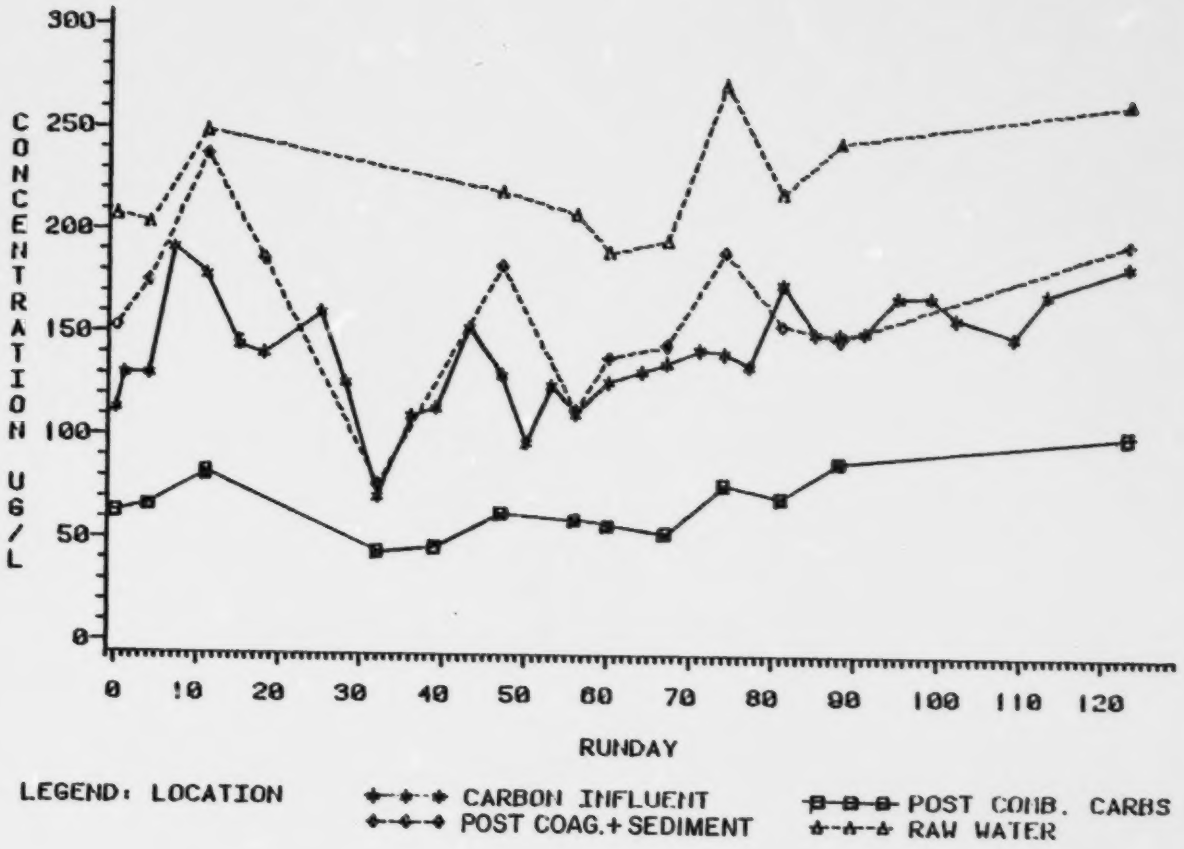


Figure 34. Run 2.—WTP three day 28.5°C THMFP concentrations.

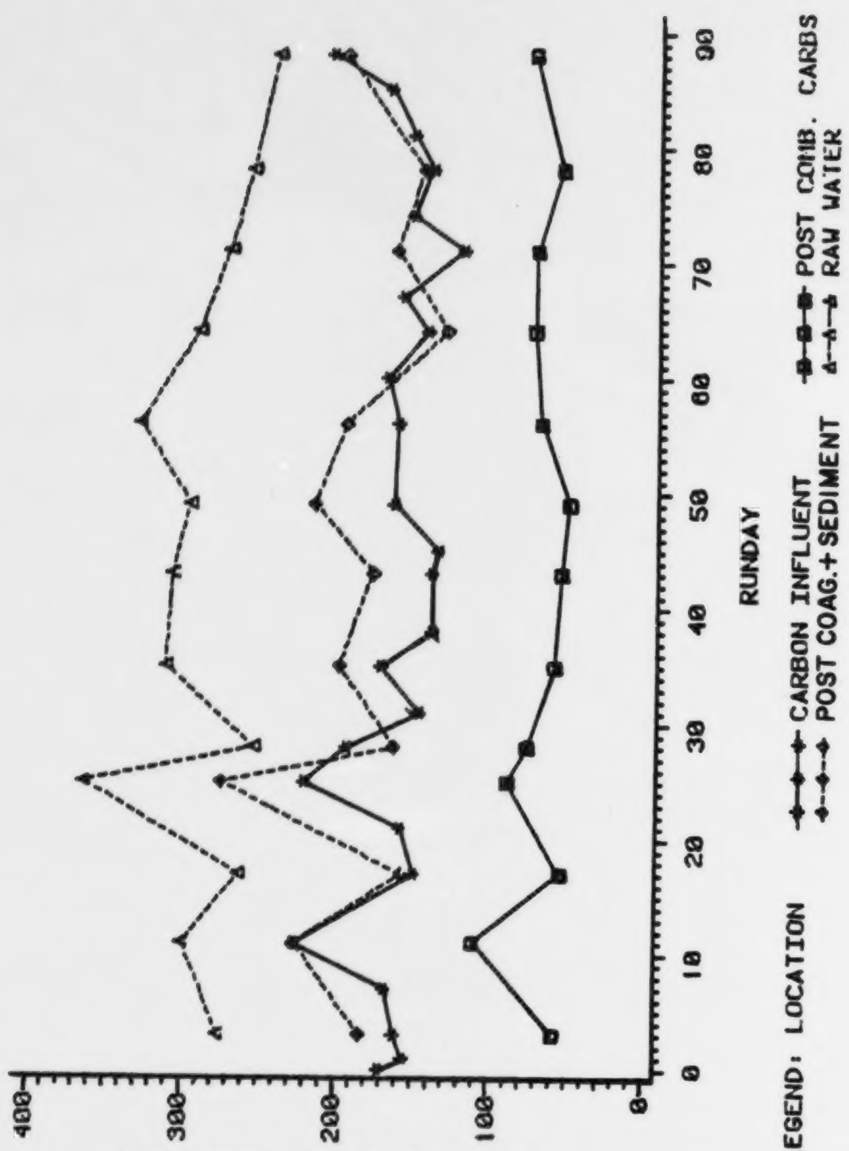


Figure 35. Run 3. — WTP three day 28.5°C THMFP concentrations.

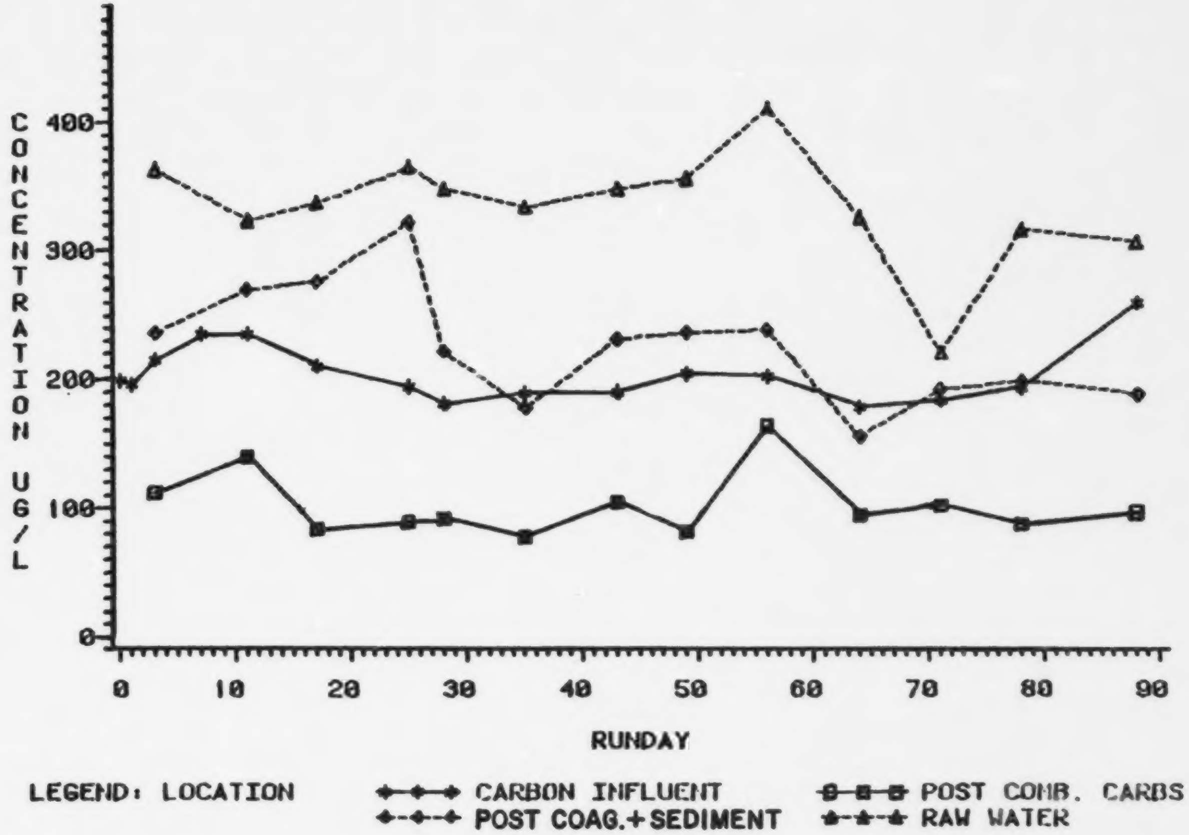


Figure 36. Run 3. — WTP seven day 28.5°C THMFP concentrations.

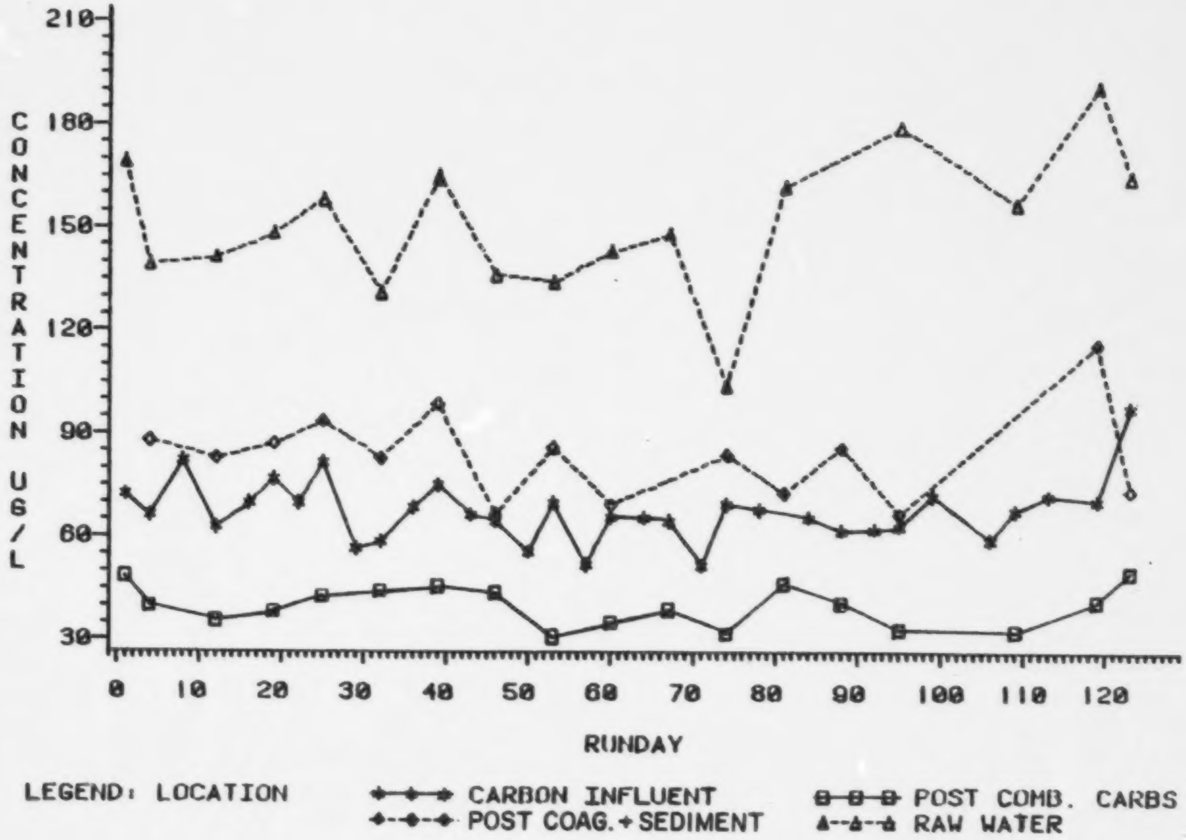


Figure 37. Run I. — WTP three day ambient THMFP concentrations.

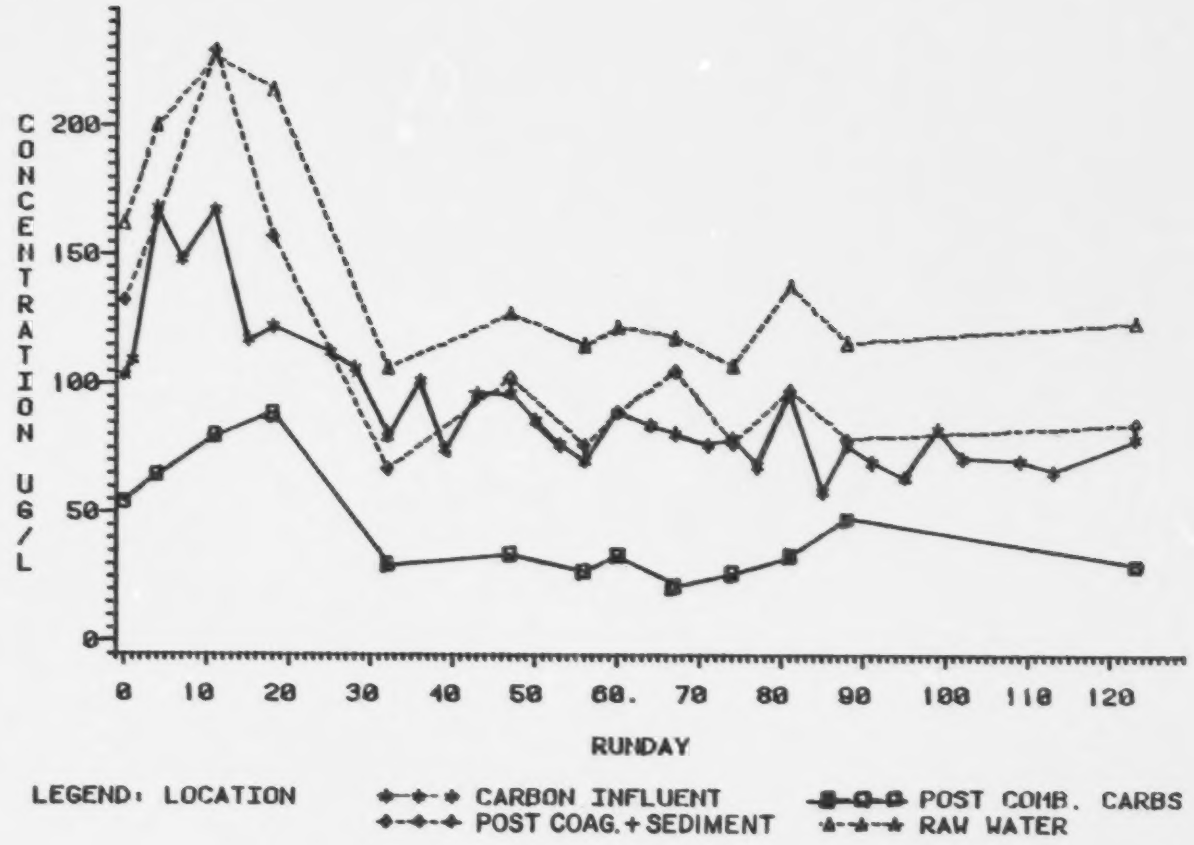


Figure 38. Run 2.— WTP three day ambient temperature THMFP concentrations.

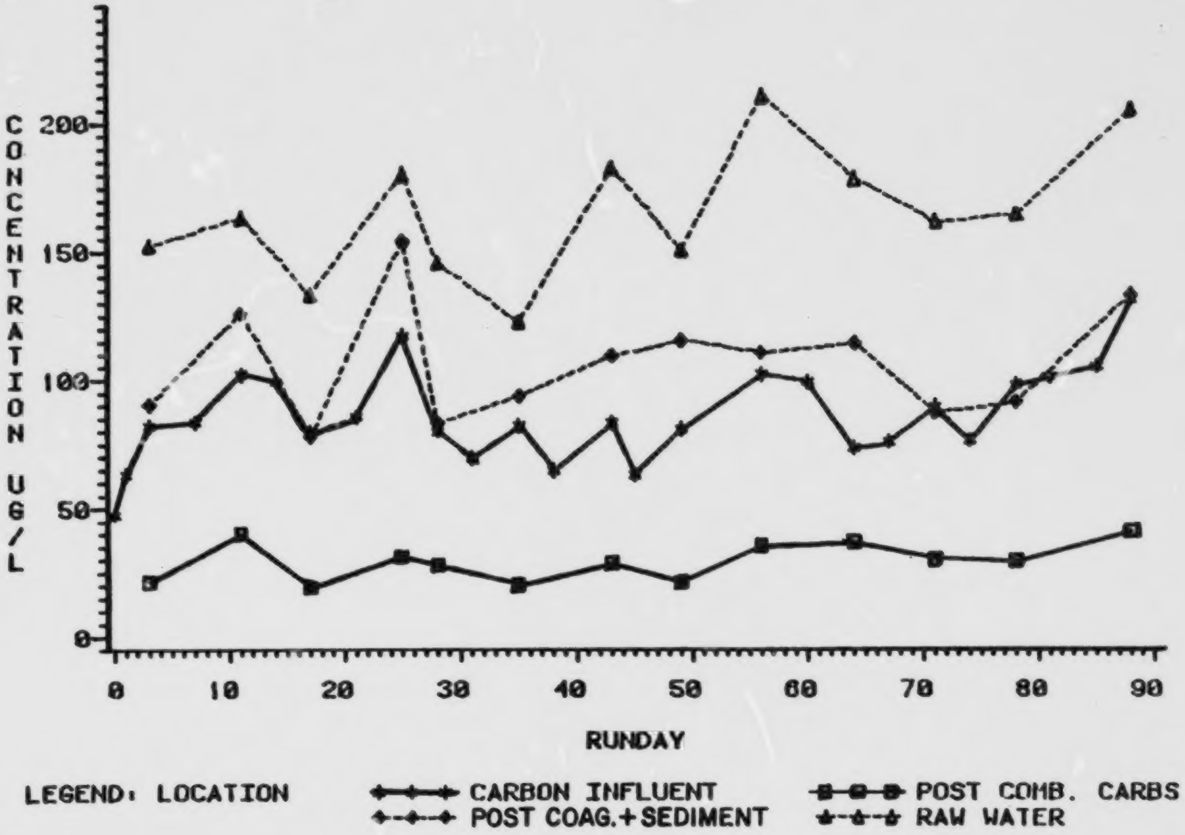


Figure 39. Run 3.— WTP three day ambient temperature THMFP concentrations.

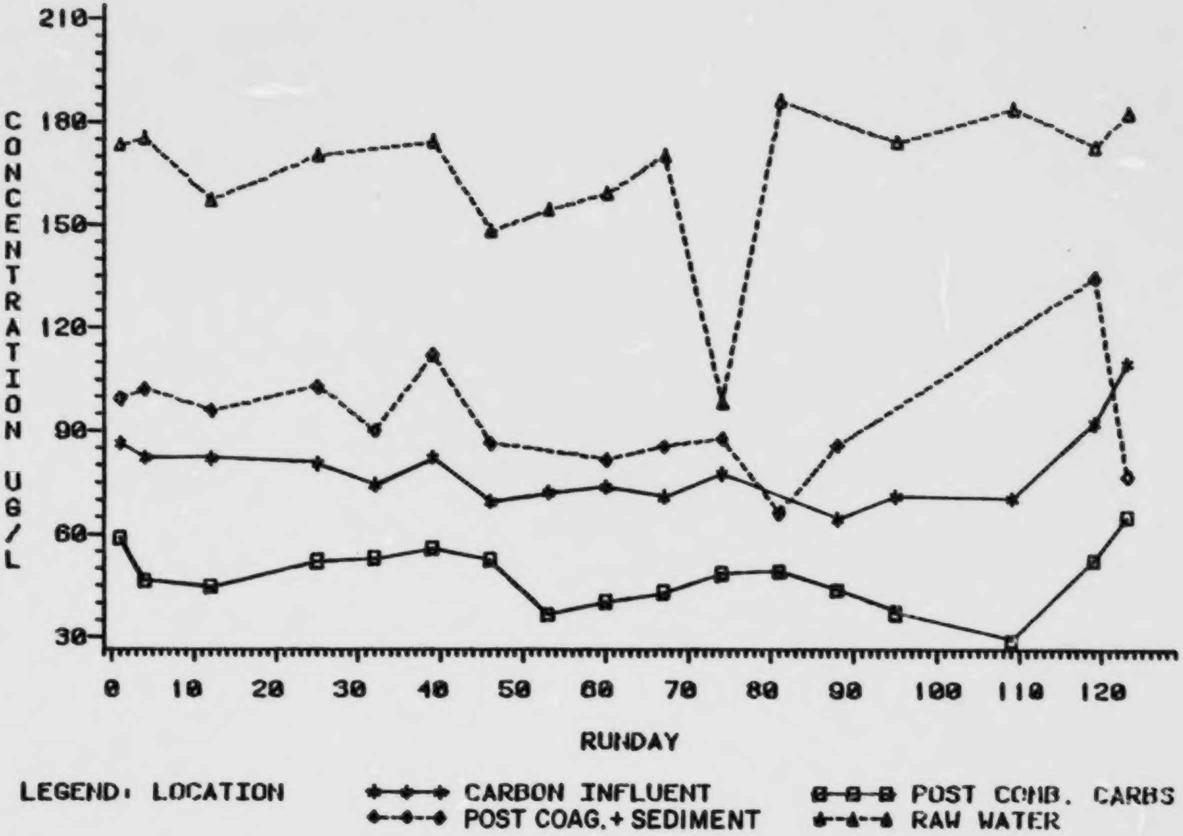


Figure 40. Run I. — WTP seven day ambient temperature THMFP concentrations.

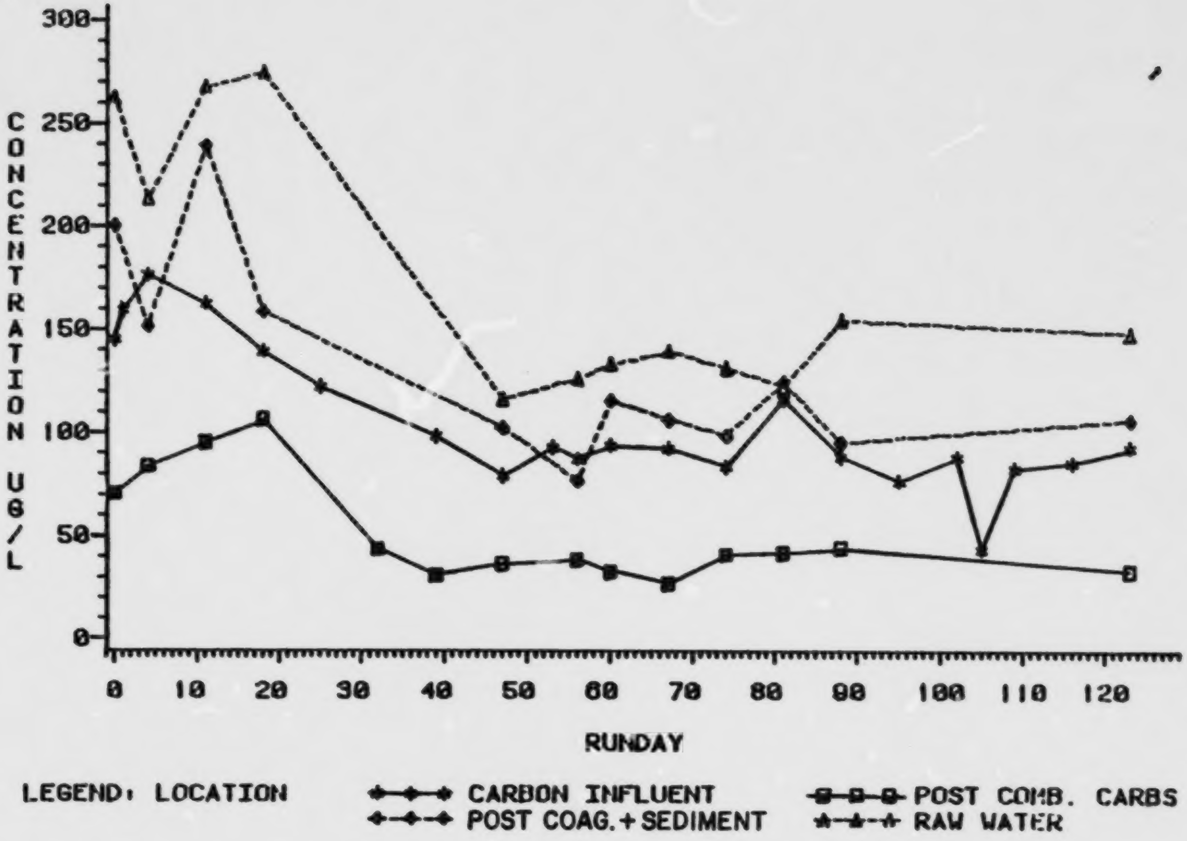


Figure 41. Run 2. — WTP seven day ambient temperature THMFP concentrations.

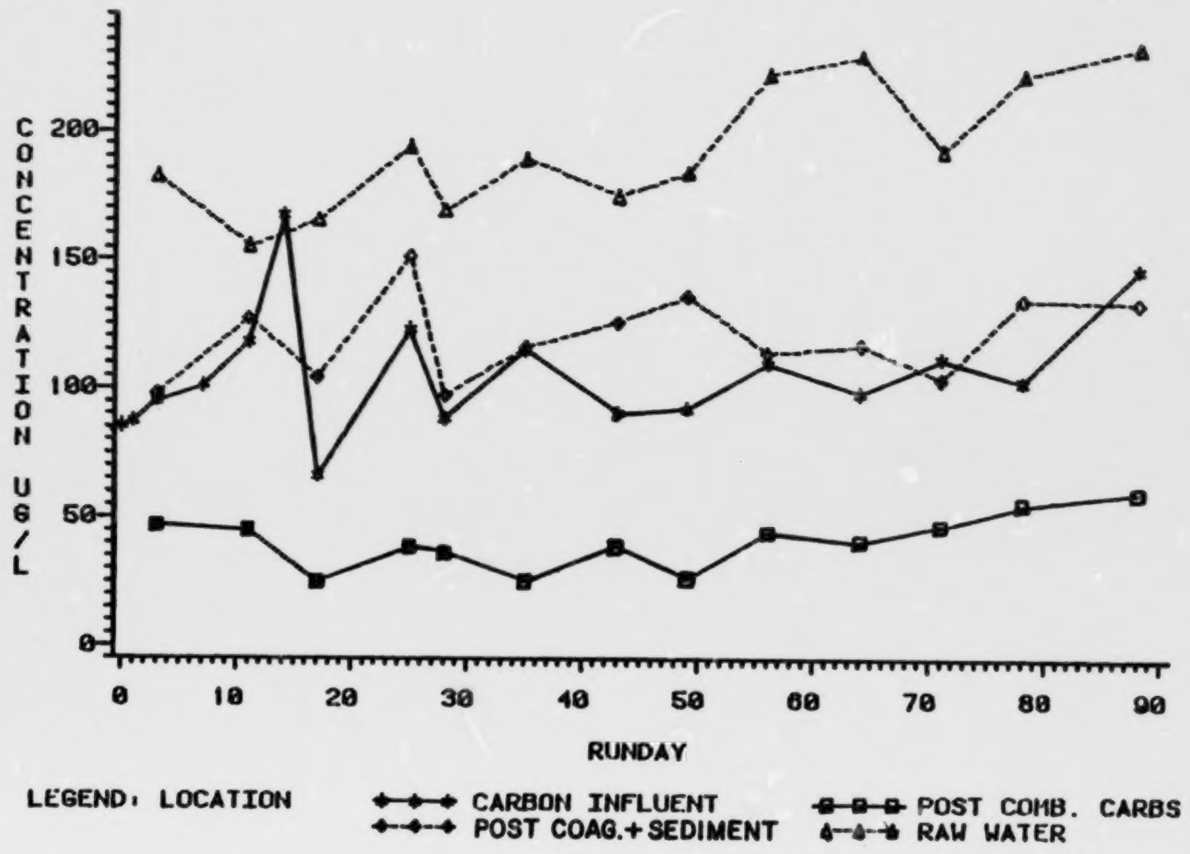


Figure 42. Run 3.— WTP seven day ambient temperature THMFP concentrations.

Color, Turbidity, pH, Total Coliform (TC), Standard Plate Count (SPC)

WTP performance for the above parameters was generally considered to be the prime indicator of proper or improper operation. Through the use of the WTP processes, a concerted effort is made to produce consistently high water quality. Apparent color is reduced through the WTP from its influent concentration of about 15 units to an effluent concentration of approximately 1 unit (Figures 43, 44 and 45).

Turbidity is likewise reduced through conventional WTP processes. The reduction in turbidity is on the order of 75%, ranging from an influent value of .5 NTU to a typical effluent value of .12 NTU (Figures 46, 47 and 48).

pH measurements, like color and turbidity are also taken daily from all WTP sample sites as an element of routine treatment operation. Raw water values of 6.0 to 6.5 are depressed to the 5.7 to 5.9 range for optimum treatment. Corrosivity control predicates a pH increase following GAC filtration to approximately 7.3 through the addition of sodium hydroxide (Figures 49, 50 and 51). The effect of the freshly reactivated GAC bed on pH is described in the test filter discussion for pH.

Bacteriological measurements for TC and SPC are made weekly on the WTP influent, sand filter influent, GAC influent and GAC effluent samples. Because of the practice of applying chlorine only after the flocculation and sedimentation phase of the WTP process, WTP influent samples are the only samples to demonstrate significant bacteriological activity. Whereas the raw samples contain TC concentrations of 2-25 colonies/100 mL and SPC of 10-100 CFU/mL, the concentrations of TC and SPC are reduced to 1/100 mL and 1-10 CFU/mL, respectively, following chlorination. Bacteriological activity in the GAC filter beds was not evaluated in the plant analyses; however, it was monitored through effluent sampling in the test filter studies.

Test Filter Data Discussion

Test filter water quality data compiled was more comprehensive than that produced for the general WTP monitoring program. Measurement parameters were essentially the same at all locations, but were performed with increased frequency in the test filter to develop GAC performance trends from one reactivation to another. As previously described, test filter performance data was used to plot breakthrough curves, percent removal, and GAC loading curves. In particular, the GAC loading graphics enabled most of the random variables to be normalized from run to run with the exception of the contact time and temperature conditions.

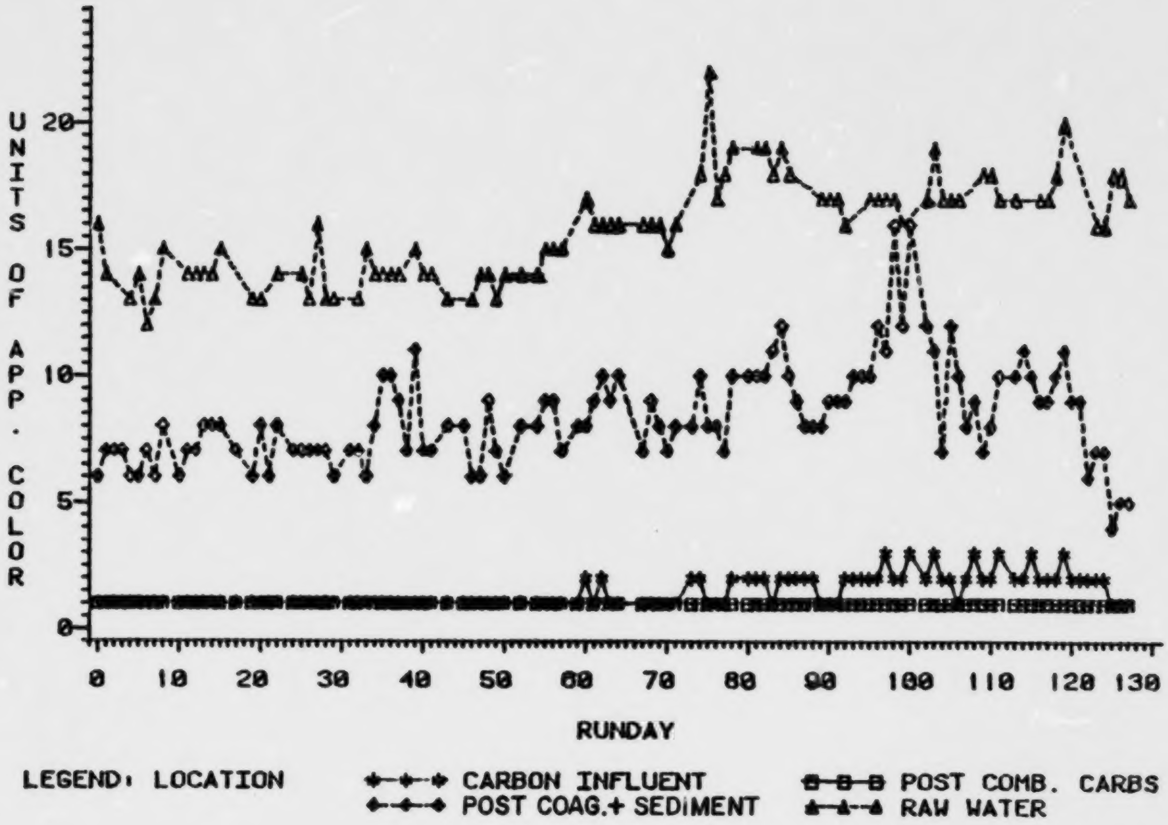


Figure 43. Run I.— WTP apparent colors.

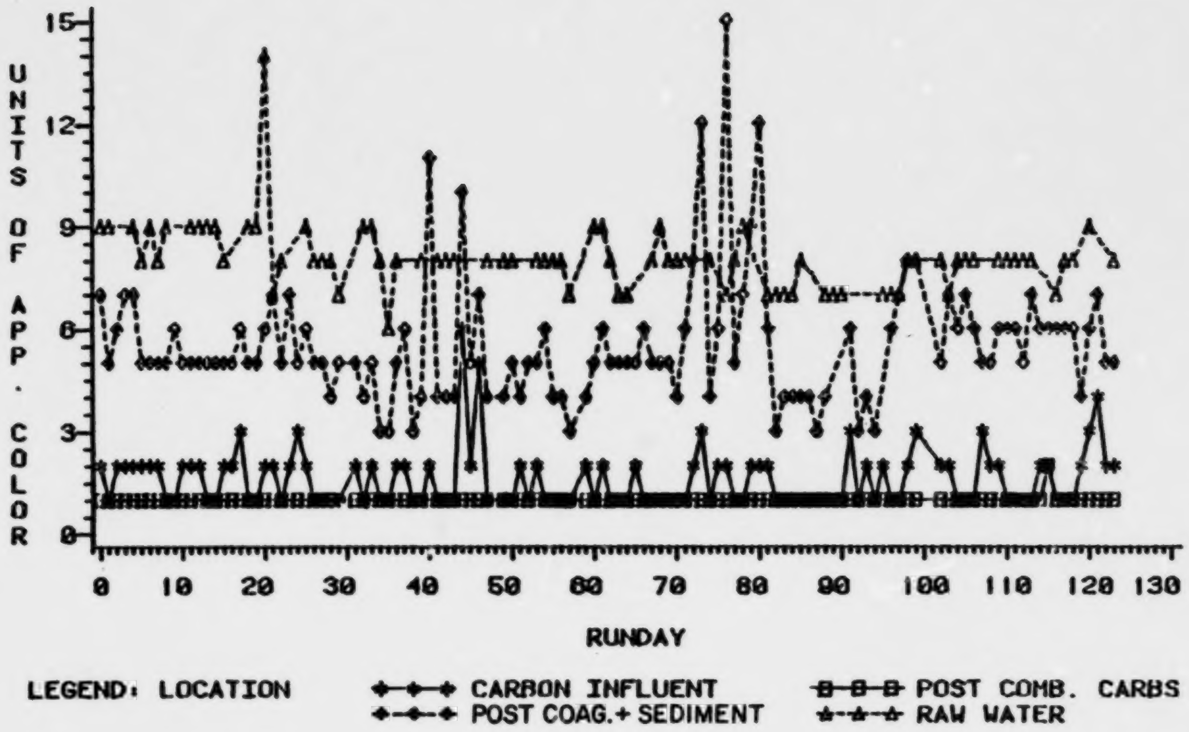


Figure 44. Run 2. — WTP apparent colors.

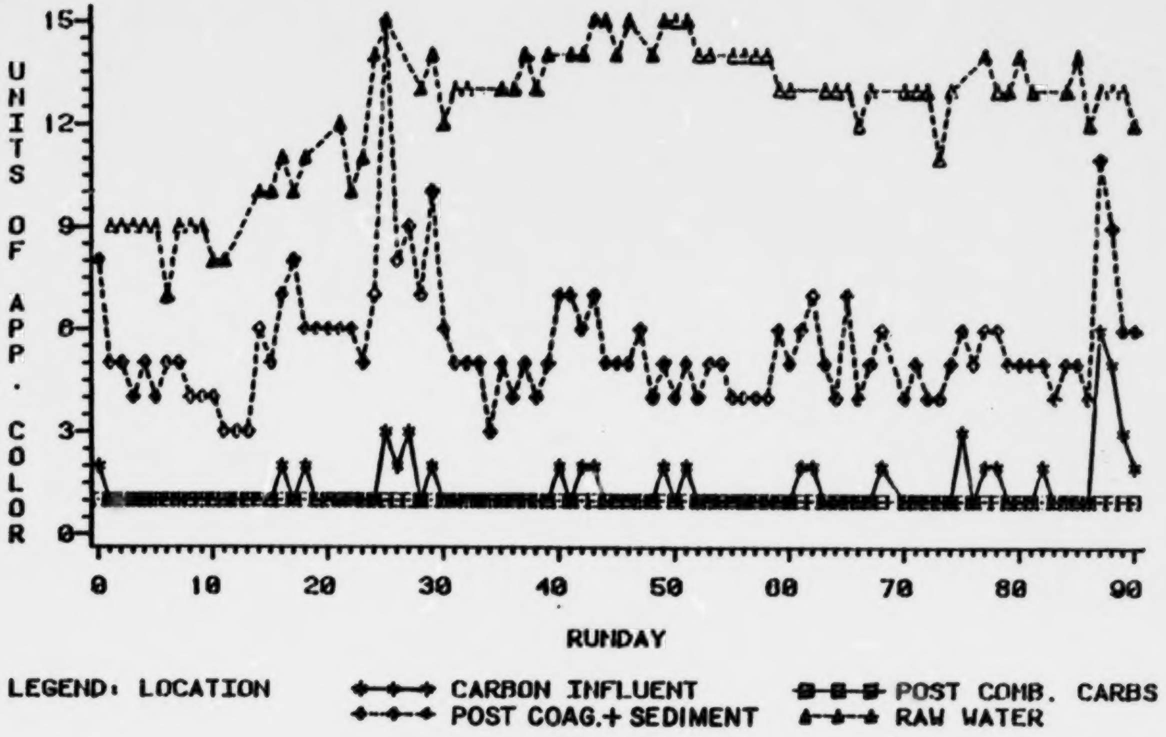


Figure 45. Run 3.—WTP apparent colors.

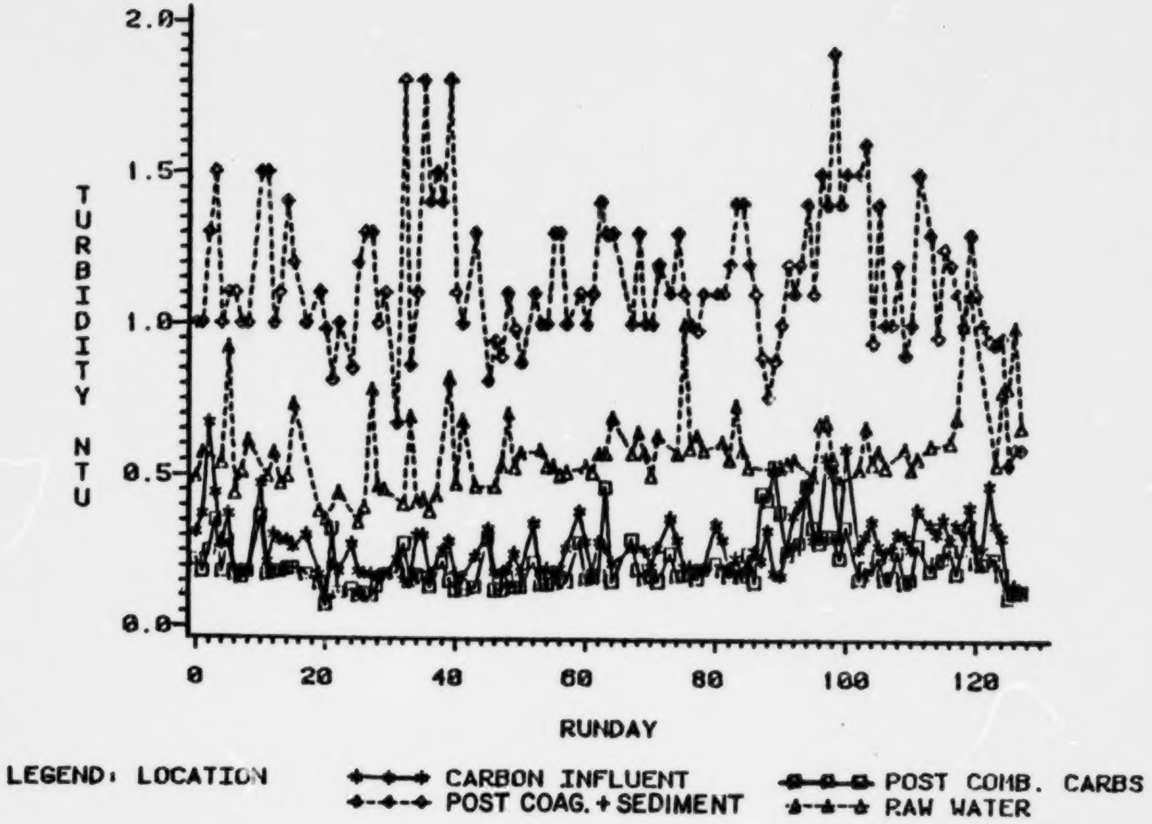


Figure 46. Run I.—WTP turbidity levels.

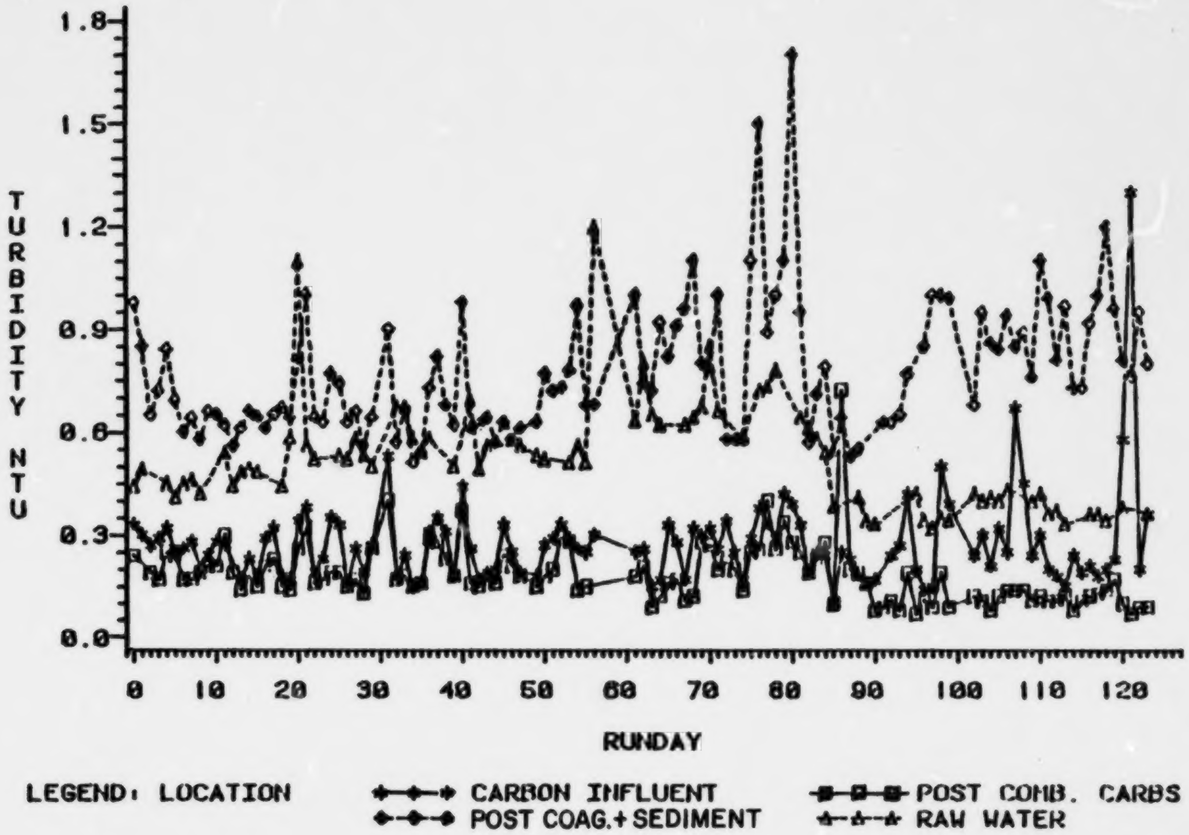


Figure 47. Run 2.— WTP turbidity levels.

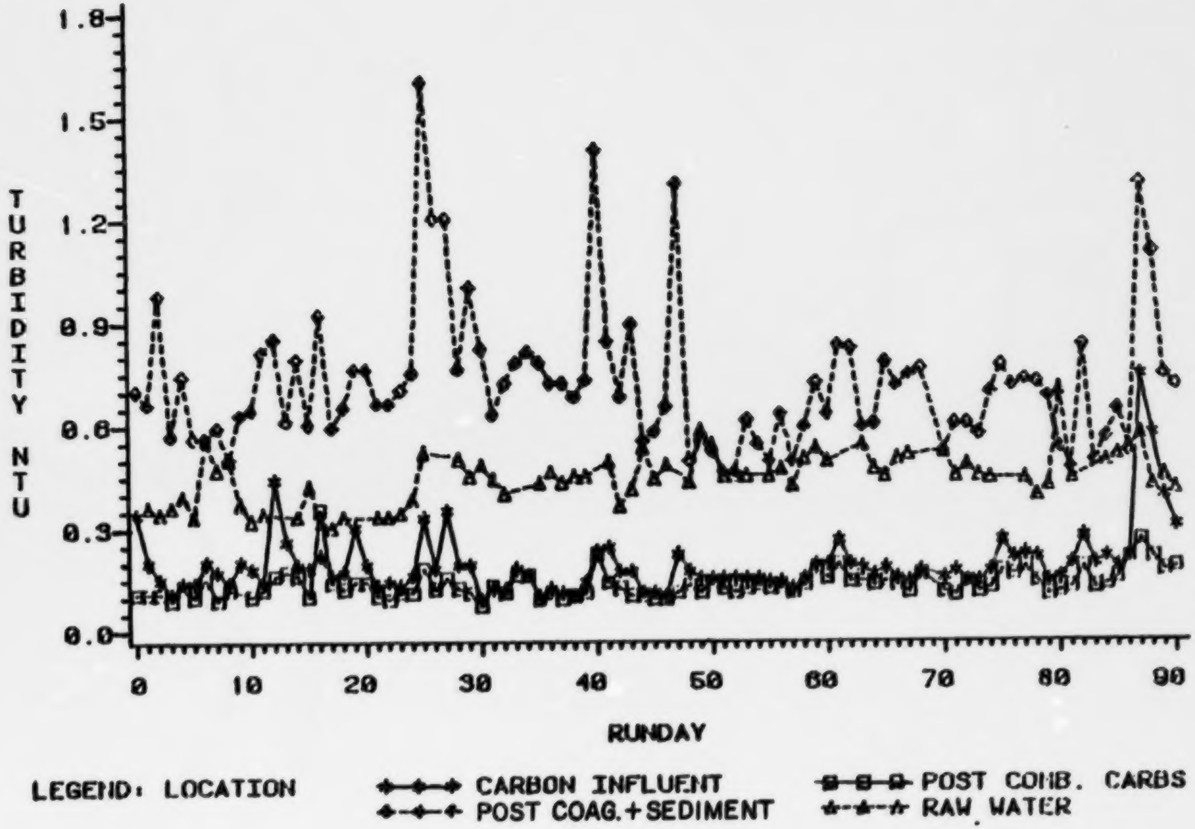


Figure 48. Run 3. — WTP turbidity levels.

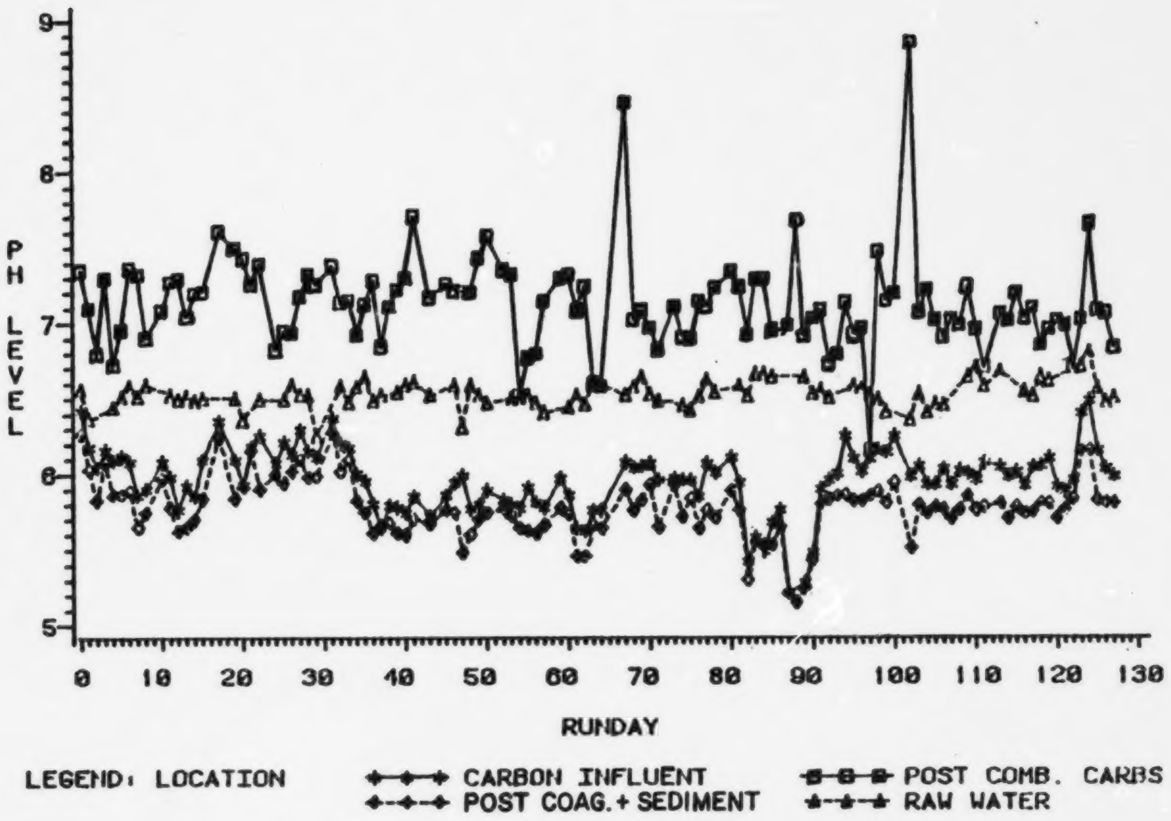


Figure 49. Run I. — WTP pH levels.

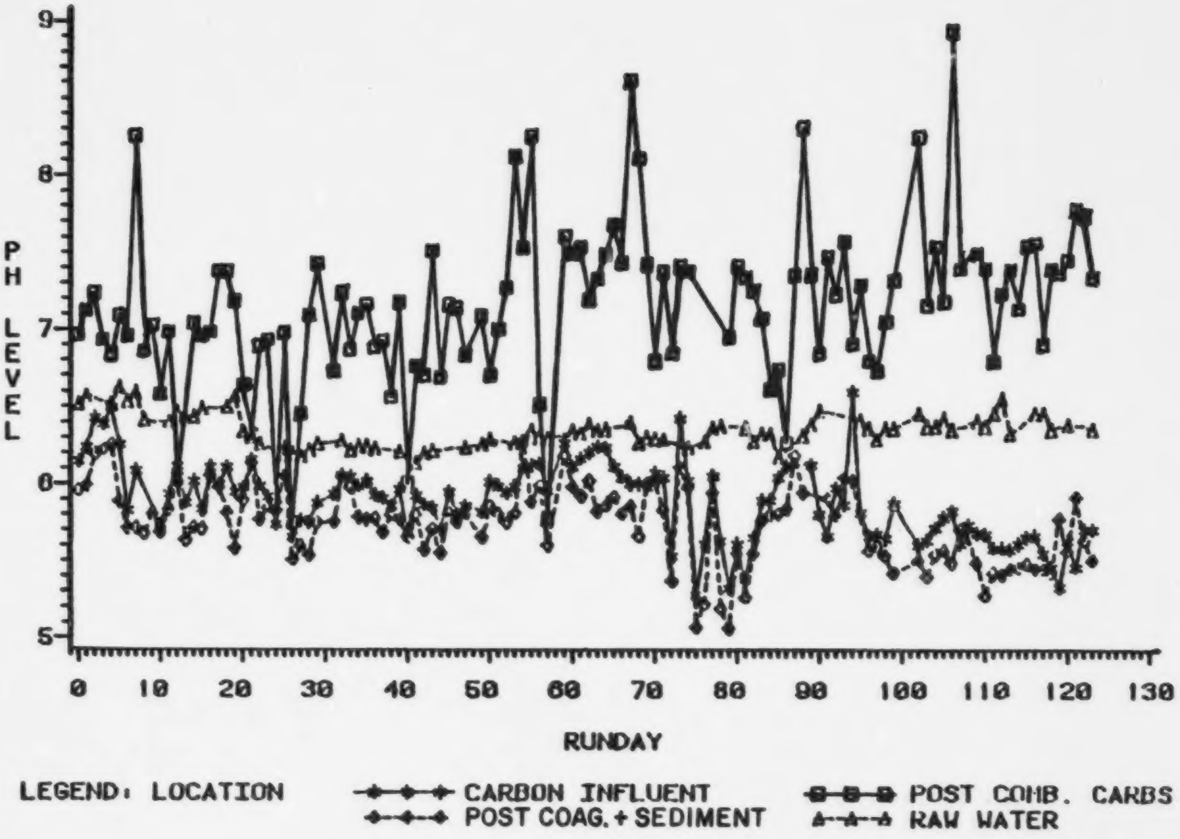


Figure 50. Run 2.—WTP pH levels.

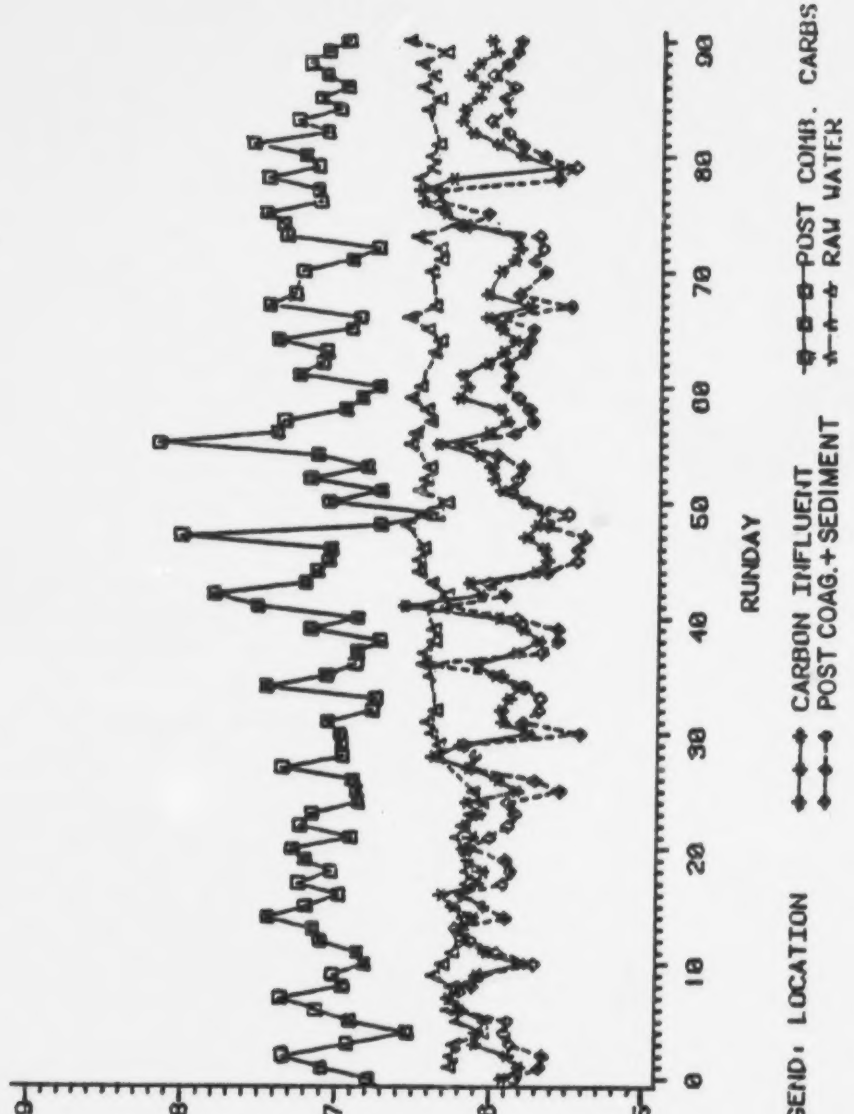


Figure 51. Run 3.— WTP pH levels.

Although these 2 variables affected the filter's performance, interrun comparisons of the GAC loading capacity for individual test parameters provided a normalized comparison of reactivation effectiveness. However, the results of this loading analysis for any single run was free of these 2 complicating factors as the temperature and contact time were the same for both halves of the test filter. GAC influent and test filter effluent concentrations are plotted together in each of the breakthrough graphics. This presentation allows the reader to visually discern the breakthrough phenomena as a function of the influent concentration. Graphic illustrations for percent removal of TOC, ITHM, etc. are based on the following equation:

$$\text{Percent Removed} = \frac{C_i - C_e}{C_i} \times 100$$

Ci - GAC Influent Concentration
Ce - GAC Effluent Concentration

A statistical analysis has been performed for each monitoring cycle for the parameters; ITHM, TOC and 3 and 7-day THMFP for both maximum and ambient temperature conditions. Table 19 contains a summary of this information and an explanation of its significance is presented in the test filter summary section.

Test filter ambient temperatures and daily flow rates during each monitoring period are presented in Figures 52, 53, 54 and 55. As discussed earlier, the similarity between runs #1 and #3 in these parameters is highly advantageous in verifying the similarity between the GAC lots studied.

Instantaneous Trihalomethane (ITHM) Adsorption Characteristics

Figures 56 to 61 present the ITHM breakthrough and percent removals for runs #1, #2, and #3. ITHM breakthrough is observed in a period of 50 to 70 days. Average daily flow rate, influent ITHM concentration, and ambient temperatures varied from run to run as did the number of reactivations of the GAC media being studied. However, runs #1 and #3 do show striking similarities in average flow rates and ambient temperature conditions (Figures 52, 53, 54 and 55). Loading rate varied, however, as the mean influent ITHM concentration in run #1 was 7 ug/l while run #3 was 12 ug/L. The overall ITHM loading during runs #1 and #3 was 120 and 140 kg GAC, respectively. Average EBCT as calculated from daily flows of 7,600 and 7,500 M^3/day for runs #1 and #3 were very similar. Consequently, the loading graphics for runs #1 and #3 (Figures 62 and 64) show particular significance as they are only minimally affected by differences in EBCT and ambient temperature.

Comparing these 2 runs, an increase of 40% in the capacity of the (1974) service GAC media after one reactivation versus

TABLE 19

PHYSICAL CHARACTERISTICS OF SPENT GAC

Property	Spent Virgin 1974 GAC	Spent Virgin 1979 GAC	Spent 1st Reactivation 1974 GAC	Spent 1st Reactivation 1979 GAC	Spent 2nd Reactivation 1974 GAC	Spent 2nd Reactivation 1979 GAC	Spent 3rd Reactivation 1974 GAC
Abrasion Number[1], % Mean	78.3	85.65	81.48	84.2	84.7	89.2	87.8
Abrasion Number[2], % Mean				84.2	84.7	89.2	87.8
Apparent Density[1] g/mL (lb/ft^3)	.659 (41.1)	.667 (41.6)	.609 (38.0)	.614 (38.3)	.603 (37.6)	.593 (37.0)	.590 (36.8)
Apparent Density[2] g/mL (lb/ft^3)	.664 (40.2)	.634 (39.6)	.630 (39.3)	.614 (38.3)	.603 (37.6)	.593 (37.0)	.590 (36.8)
Ash[1] Percent	7.07	5.42	6.99	6.02	6.82	6.17	6.94
BET[1] M^2/g		814.03	791.4	852.3	838.7	832.6	757.9
Iodine Number[1] mg/g	583	780	798	763	720	759	743
Iodine Number[2] mg/g	530			763	720	759	743
Mean Particle Diameter[1] mm	1.42	1.44	1.37	1.37	1.34	1.37	1.33
Mean Particle Diameter[2] mm	1.49			1.39	1.37	1.39	1.31
Mod Phenol Value[1] Westvaco mg/L	37.2	25.3	29.3	24.2	26.3	20.9	23.6
Molasses Decolorizing Index[1] DI/g	2.0	3.8	3.4	4.2	4.1	4.7	4.7
Molasses Decolorizing Index[2] DI/g	1			4.2	4.1	4.7	4.7
Volatile Matter[1] Percent	12.2	14.93	13.52	10.4	10.4	8.9	9.0

1. Data shown compiled from analyses performed by or under the auspices of Dr. Stan Smith, Doraville, GA.
2. Data shown compiled from analyses performed by the MWW.
3. All samples represent composited GAC samples taken from the test filter.
4. GAC evaluated is Westvaco 8 x 30 WVW.

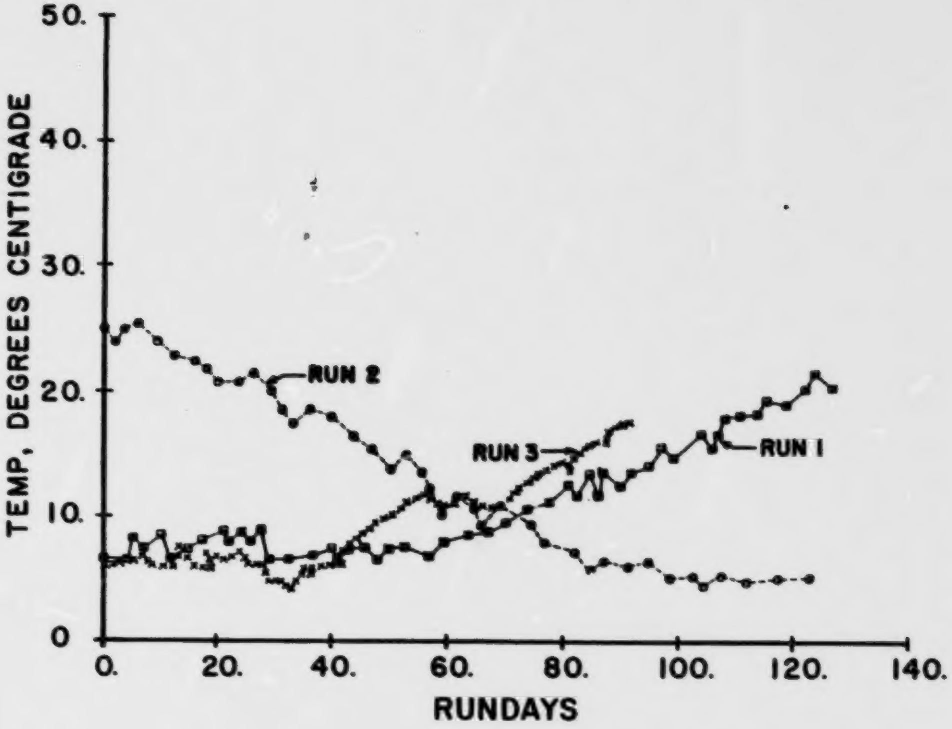


Figure 52. Runs 1, 2 & 3.— Ambient water temperature.

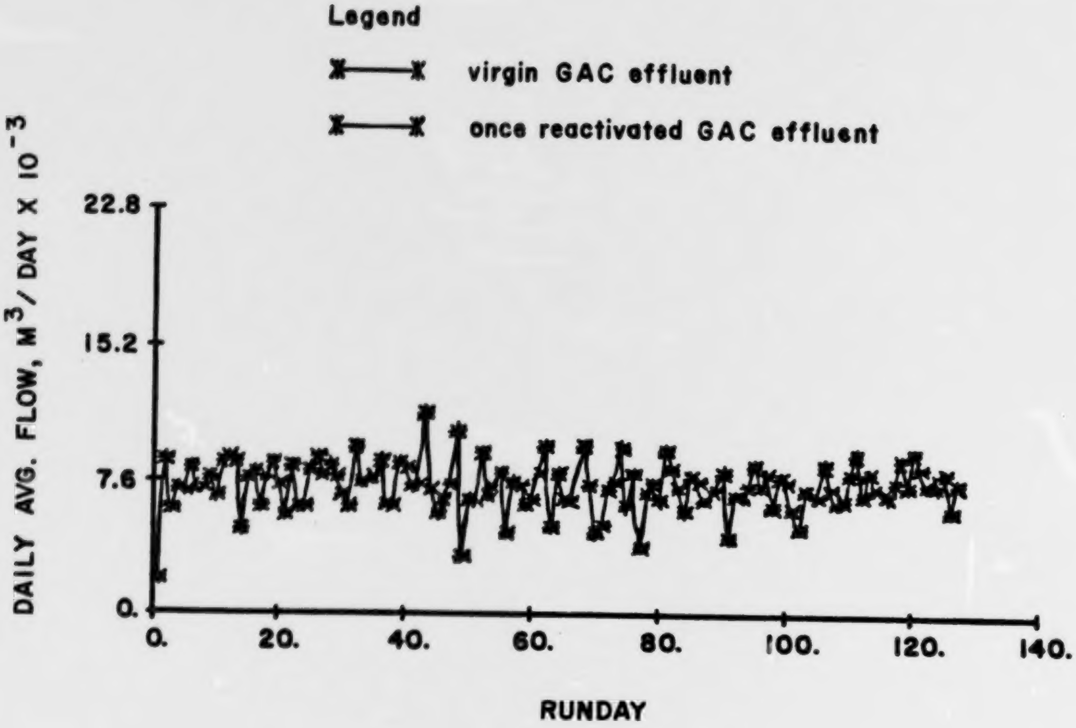


Figure 53. Run I. — Test filter bed daily avg. flow.

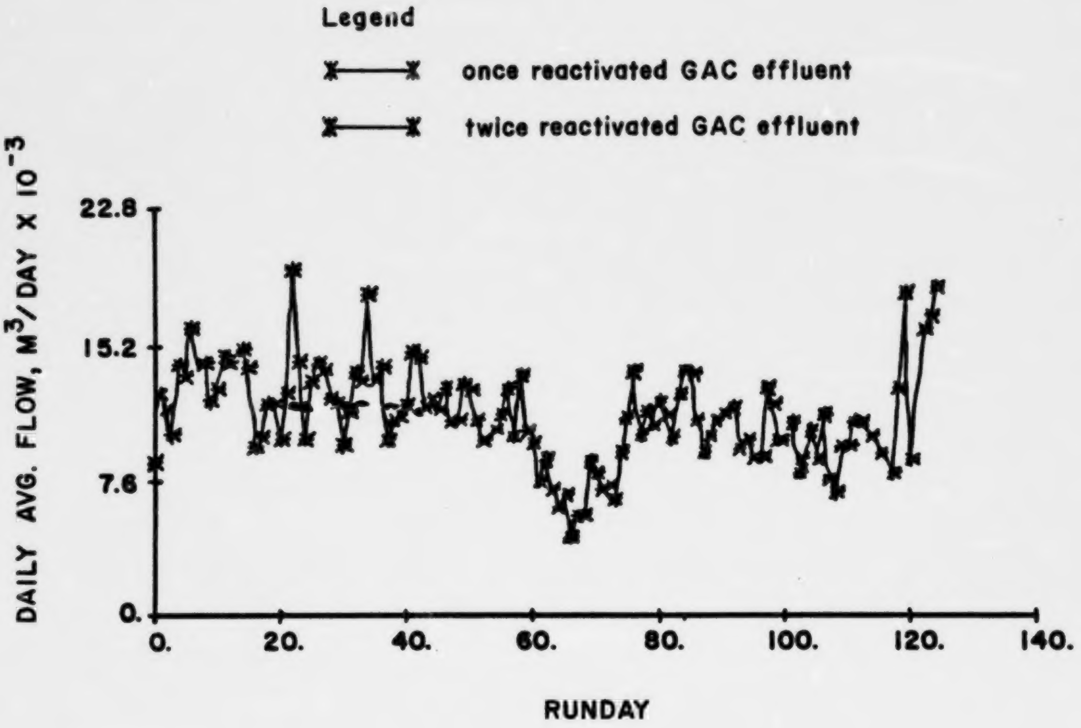


Figure 54. Run 2. — Test filter bed daily avg. flow.

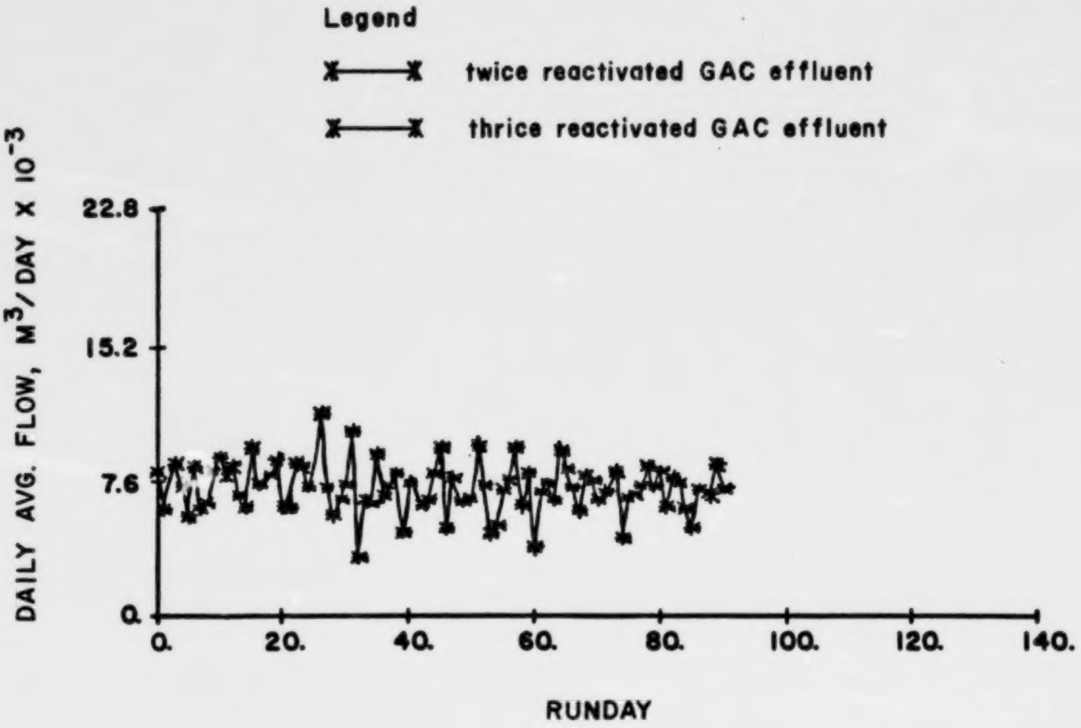


Figure 55. Run 3.— Test filter bed daily avg. flow.

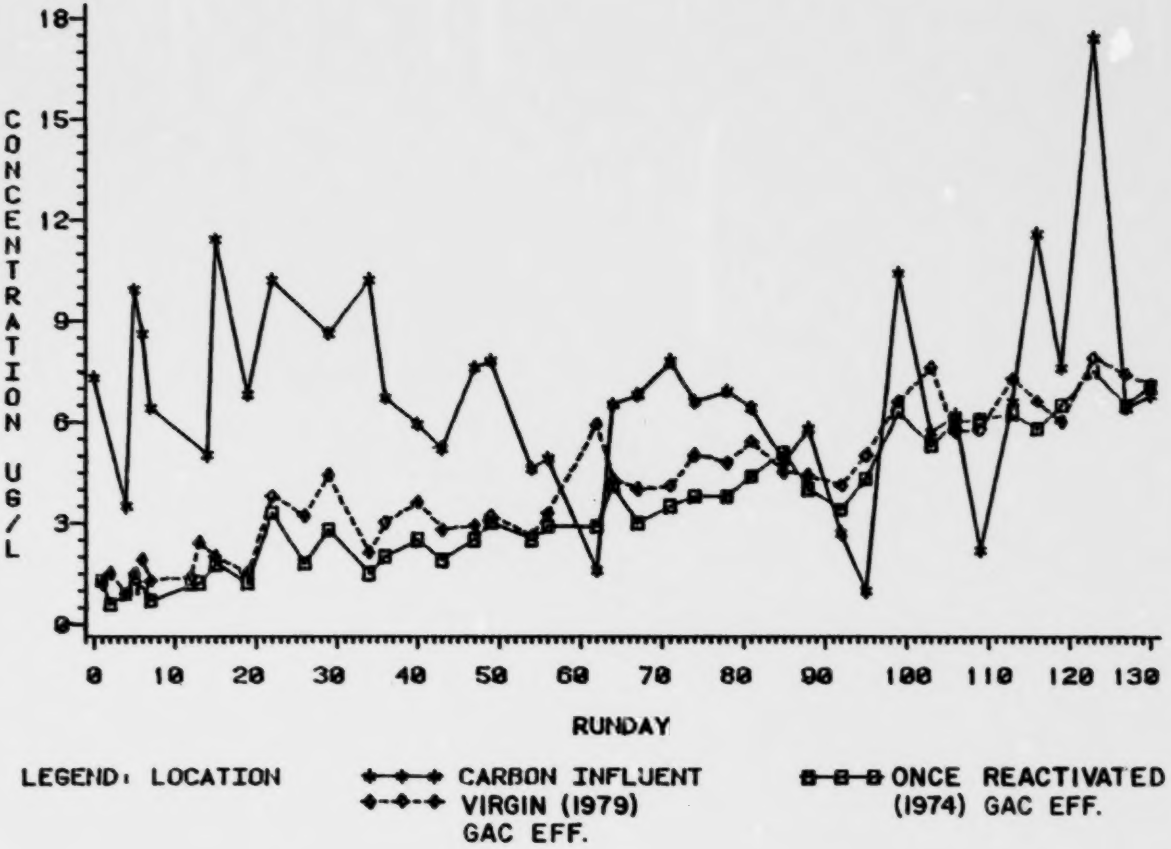


Figure 56. Run I.— Test filter ITHM breakthrough curves.

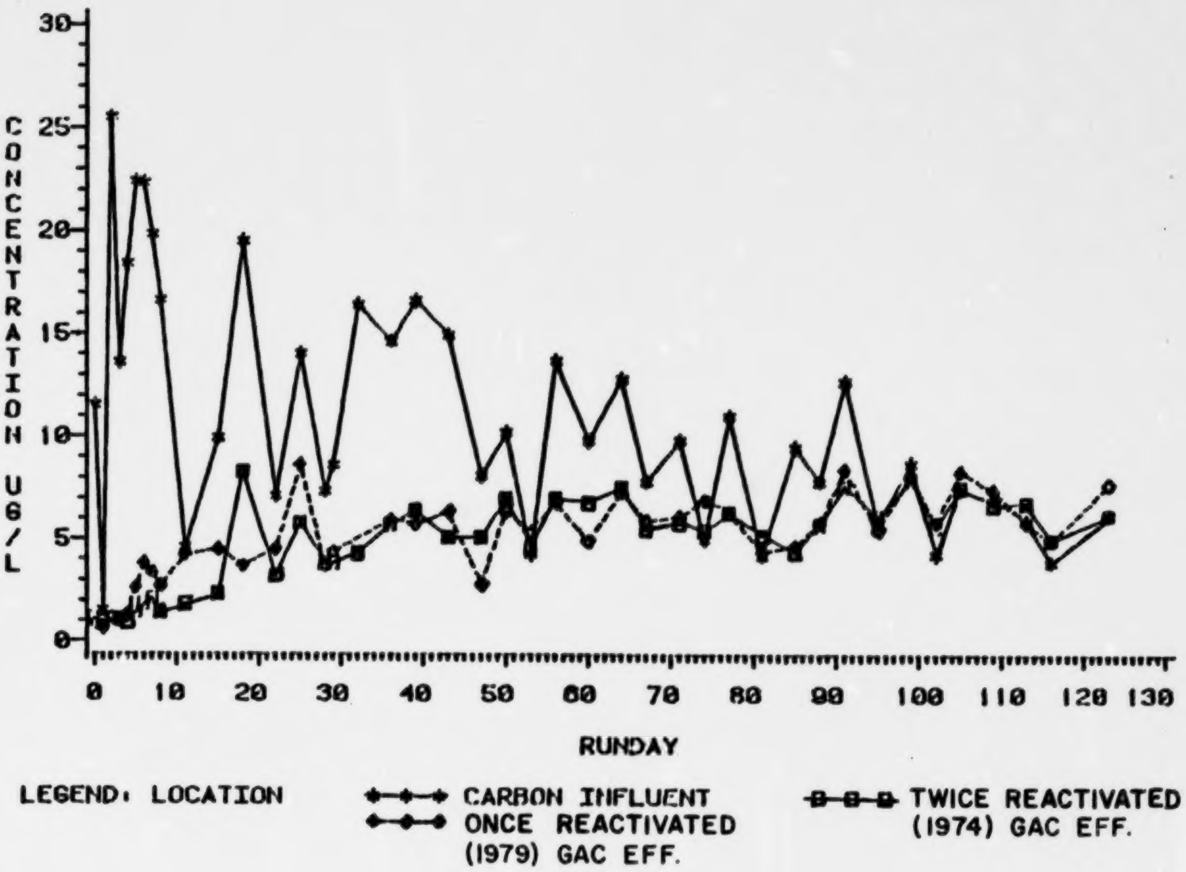


Figure 57. Run 2.— Test filter ITHM breakthrough curves.

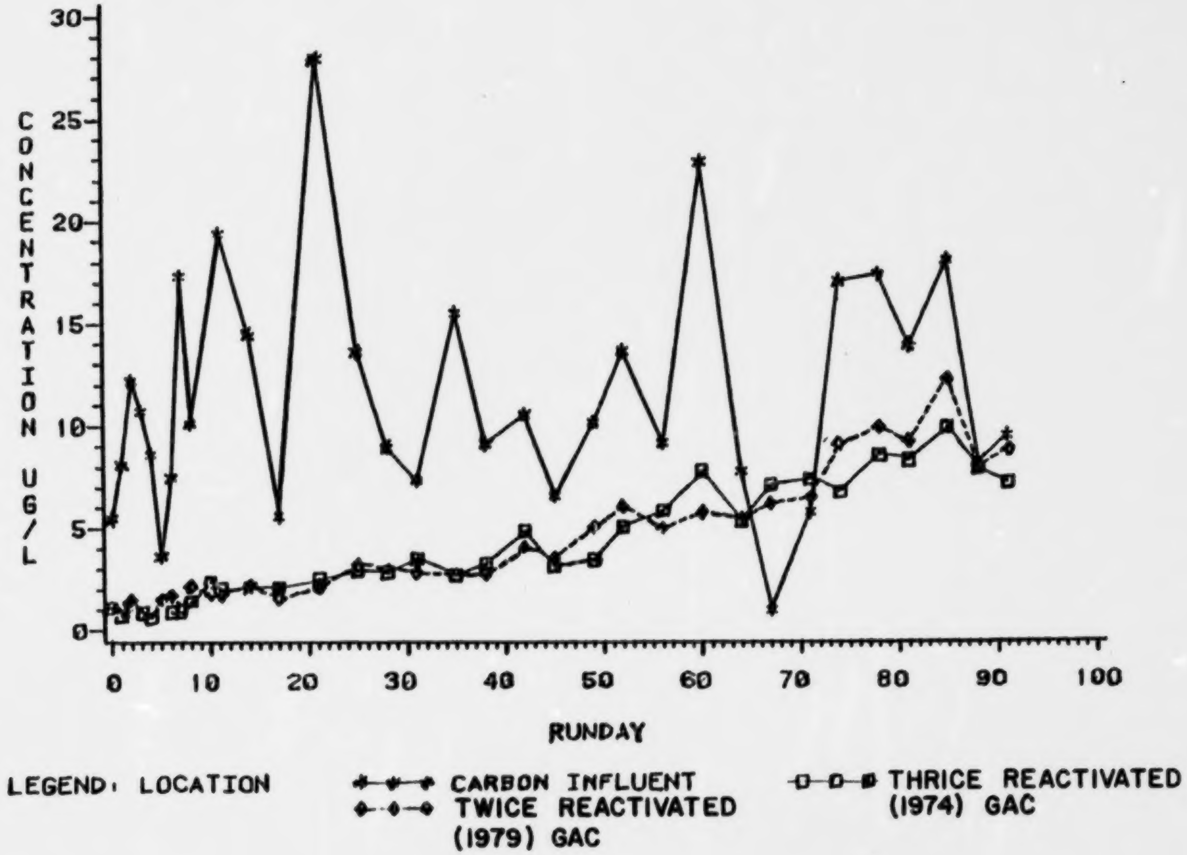


Figure 58. Run 3.— Test filter ITHM breakthrough curves.

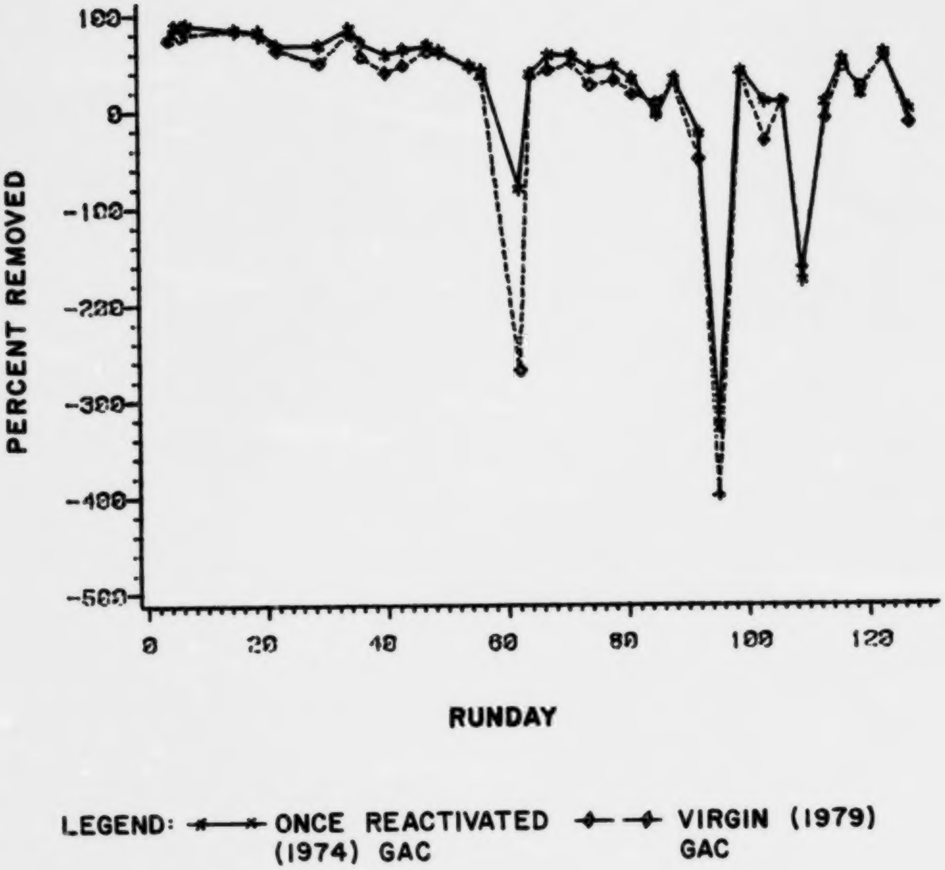


Figure 59. Run I. — Test filter percent removals for ITHM.

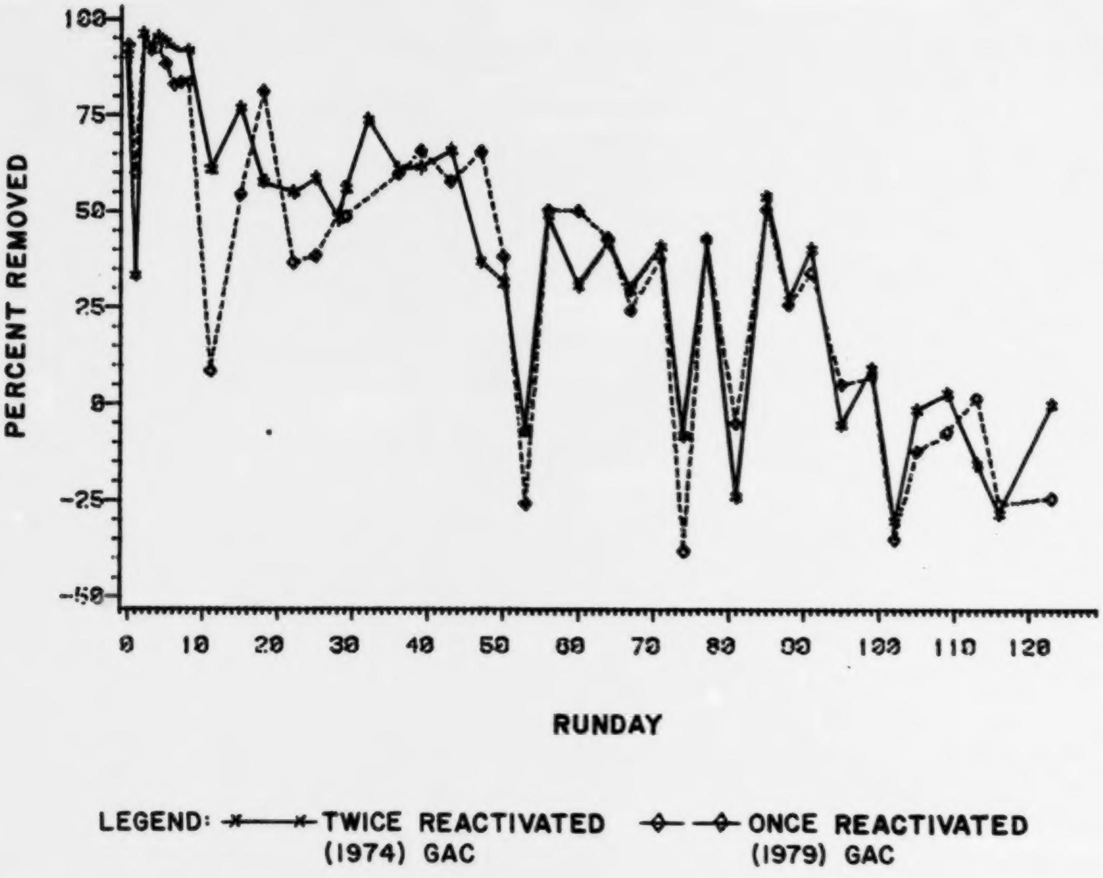


Figure 60. Run 2.— Test filter percent removals for ITHM.

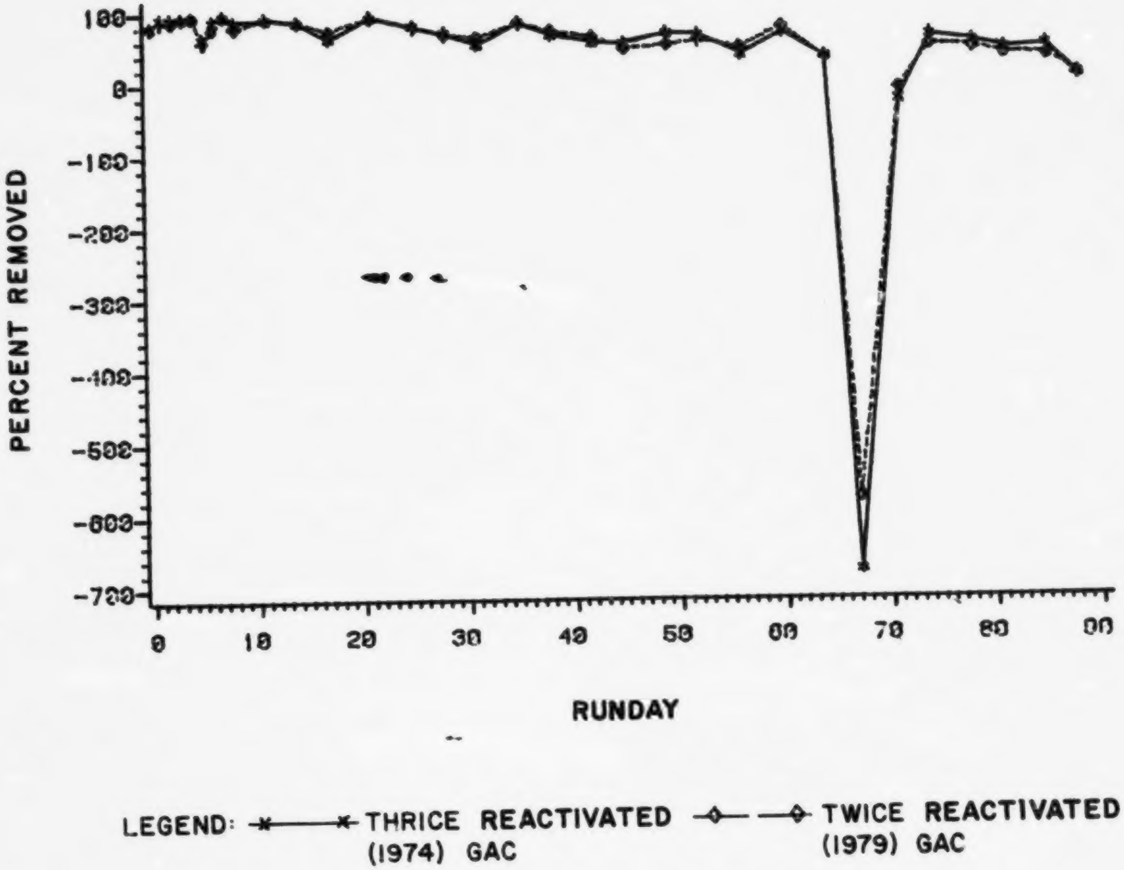


Figure 61. Run 3.—Test filter percent removals for ITHM.

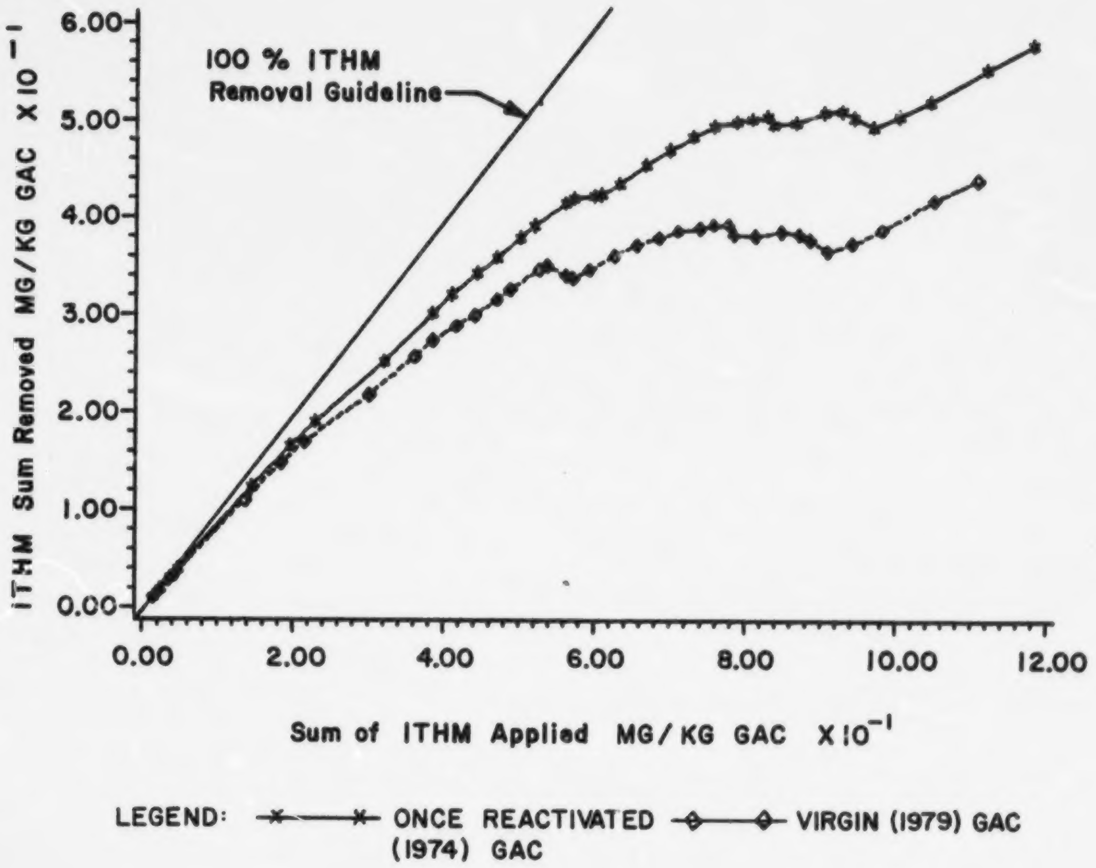


Figure 62. Run I.—Test filter loadings for ITHM.

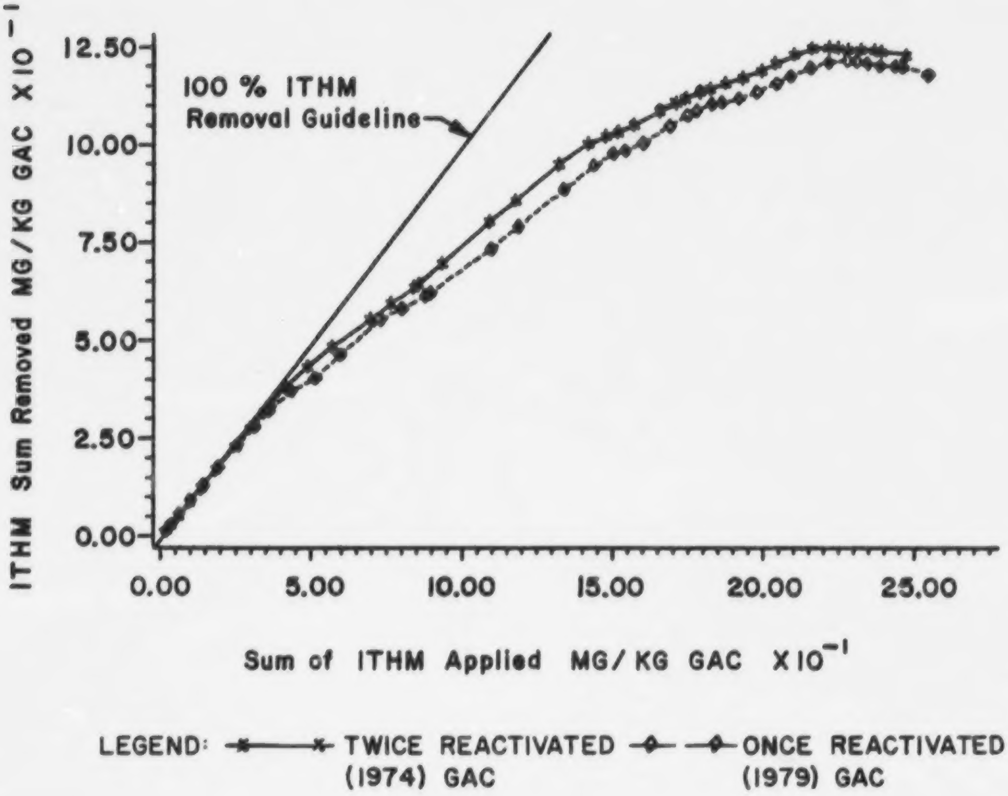


Figure 63. Run 2.—Test filter loadings for ITHM.

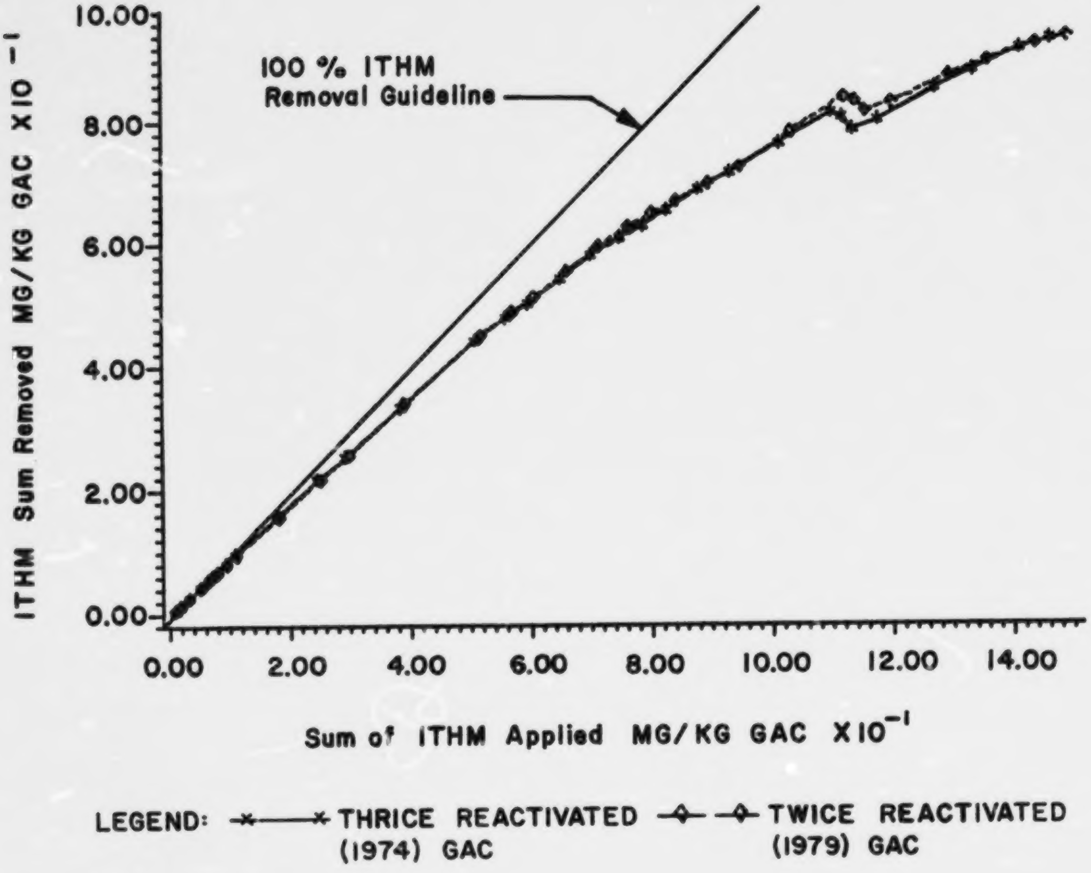


Figure 64. Run 3.—Test filter loadings for ITHM.

the same media after 3 reactivations is seen. The sum removed value of 57 mg/kg GAC in run #1 is increased to 80 mg/kg GAC in run #3 at the 120 mg/kg point or applied loading (Figure 65). Likewise, a comparison of the capacity of virgin GAC (run #1) versus the same GAC material at 2 reactivations (run #3) shows the following relative increase in capacity. At 112 mg/kg of applied loading, it was observed that only 42 mg/kg of ITHM was removed in run #1, while 80 mg/kg had been adsorbed in run #3 (Figure 66). Improved adsorptive performance was seen in the test filter even though average influent concentration of ITHM was higher in run #3 than in run #1. Run #2 was made under substancially different ambient temperature and EBCT conditions than either run #1 or run #3. The trend towards improved adsorptive capacity following reactivation was observed during run #3 nonetheless. An improved loading capacity of 80% for the once reactivated (1979) GAC and 50% for the twice reactivated (1974) were observed at the 120 mg/kg point of applied loading (Figure 65 and 66).

Total Organic Carbon (TOC) Adsorption Characteristics

TOC adsorption demonstrated generally improved and more uniform behavior with progressive reactivation. The TOC breakthrough and percent removal curves indicate that the maximum GAC capacity for TOC was not reached in any of the 3 monitoring runs (Figures 67 to 72). Instead, a steady state removal condition for TOC was reached after approximately 70 days for all 3 runs (Figures 70 to 72). In run #1, following the 70 run day, steady state reduction in TOC concentration was about 30% for virgin GAC and about 40% for once reactivated GAC (Figure 70). Following run day 70, run #2 indicated a steady state removal of about 25% for both once and twice reactivated GAC (Figure 71). Run #3 realized a steady state TOC removal of nearly 45% for both twice and thrice reactivated GAC following run day 70 (Figure 72).

Additionally, run #1 and #3 behaved according to the pattern established with ITHM of improved adsorptive capacity following reactivation (Figure 72 to 77). However, run #2, either due to variances in temperature, loading or nature of TOC species, was noticeably lower in its steady state removal percentages for TOC (Figure 71).

GAC influent TOC concentrations were in the 2.1 to 3.1 mg/l range during the 3 monitoring runs (Figures 67 to 69). Run #3 ended with influent concentrations exceeding this range without any noticeable effect on the steady state removal percentages.

Trihalomethane Formation Potential (THMFP)

The concentration of 7-day maximum THMFP influent to the test filter bed for runs #1 and #2 (Figure 89 and 90) is in the 130 to 200 ug/l range. The 3-day analysis was found to average about 30 ug/l less over runs #1 and #2 (Figures 78 and 79).

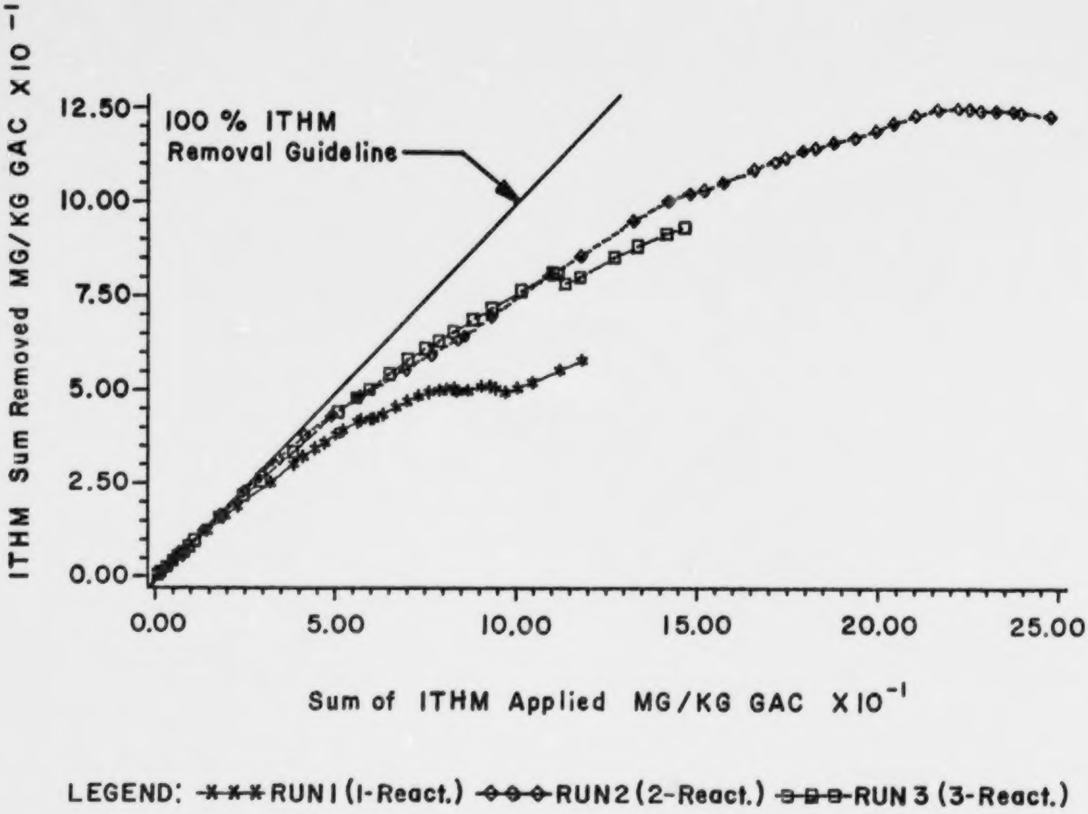


Figure 65. Interun ITHM comparison for 1974 (service) GAC.

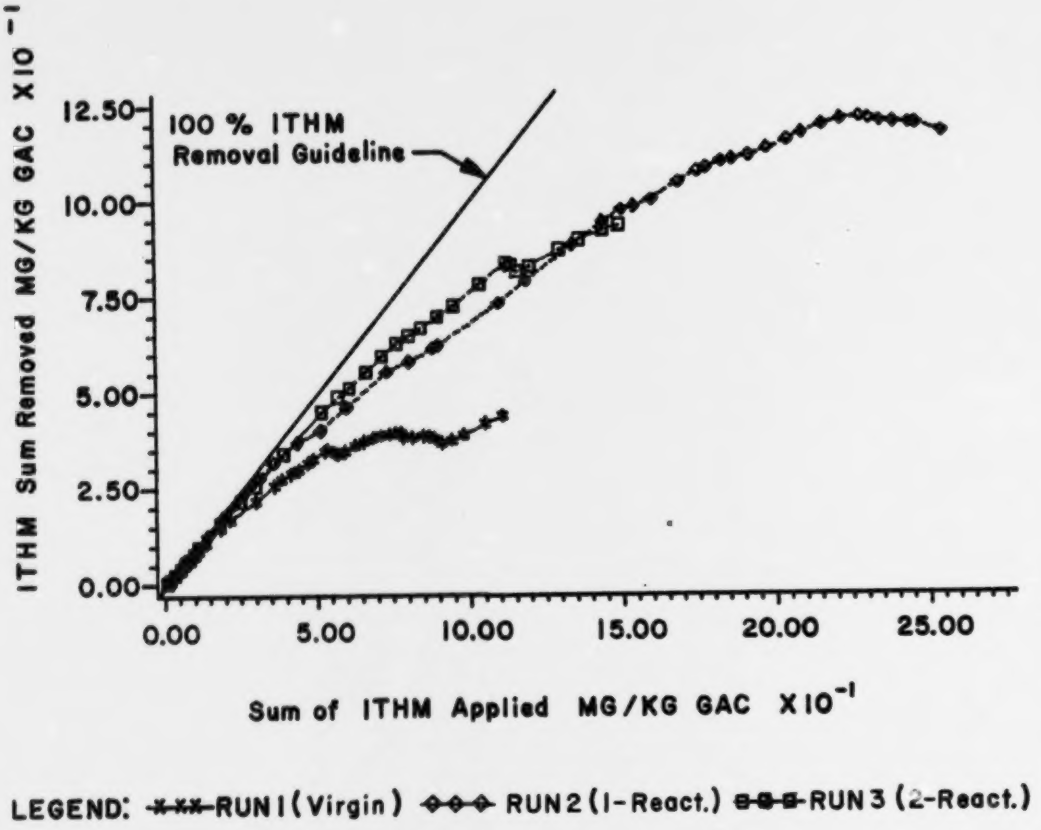


Figure 66. Interun ITHM comparison for 1979 (virgin) GAC.

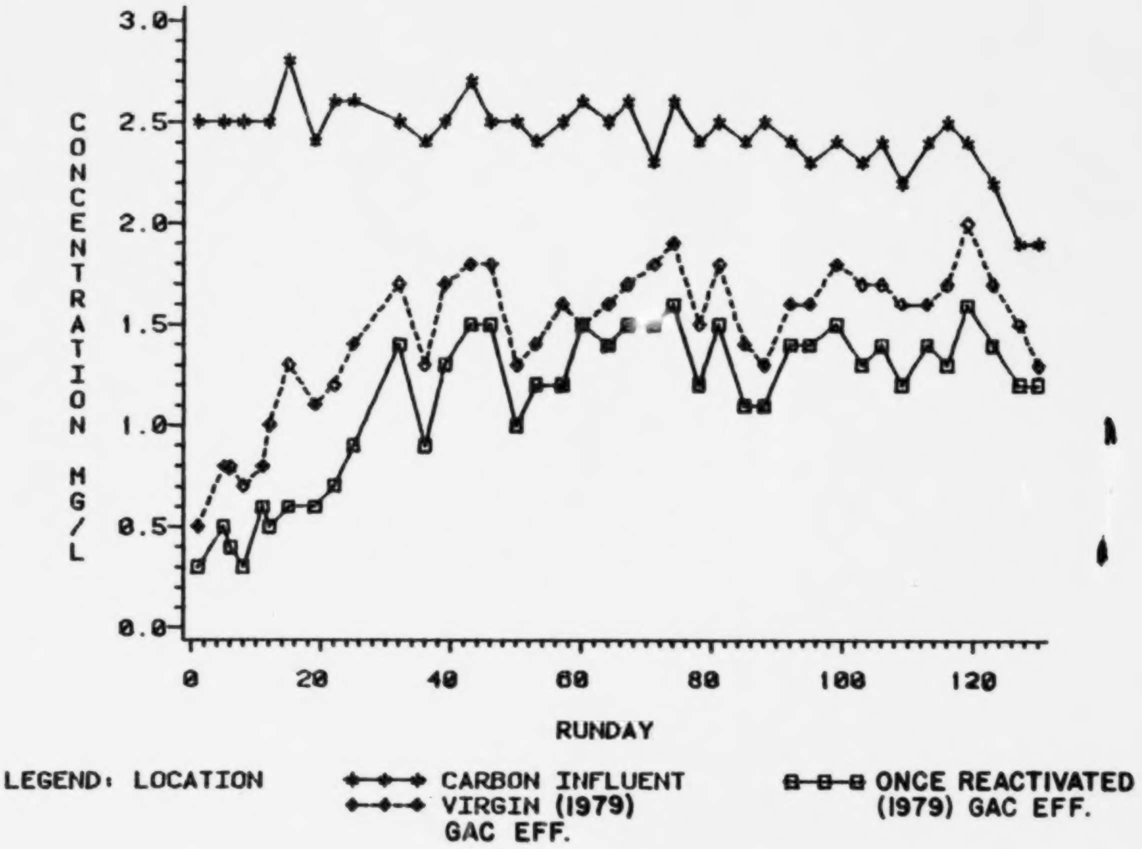


Figure 67. Run I.— Test filter TOC breakthrough curves.

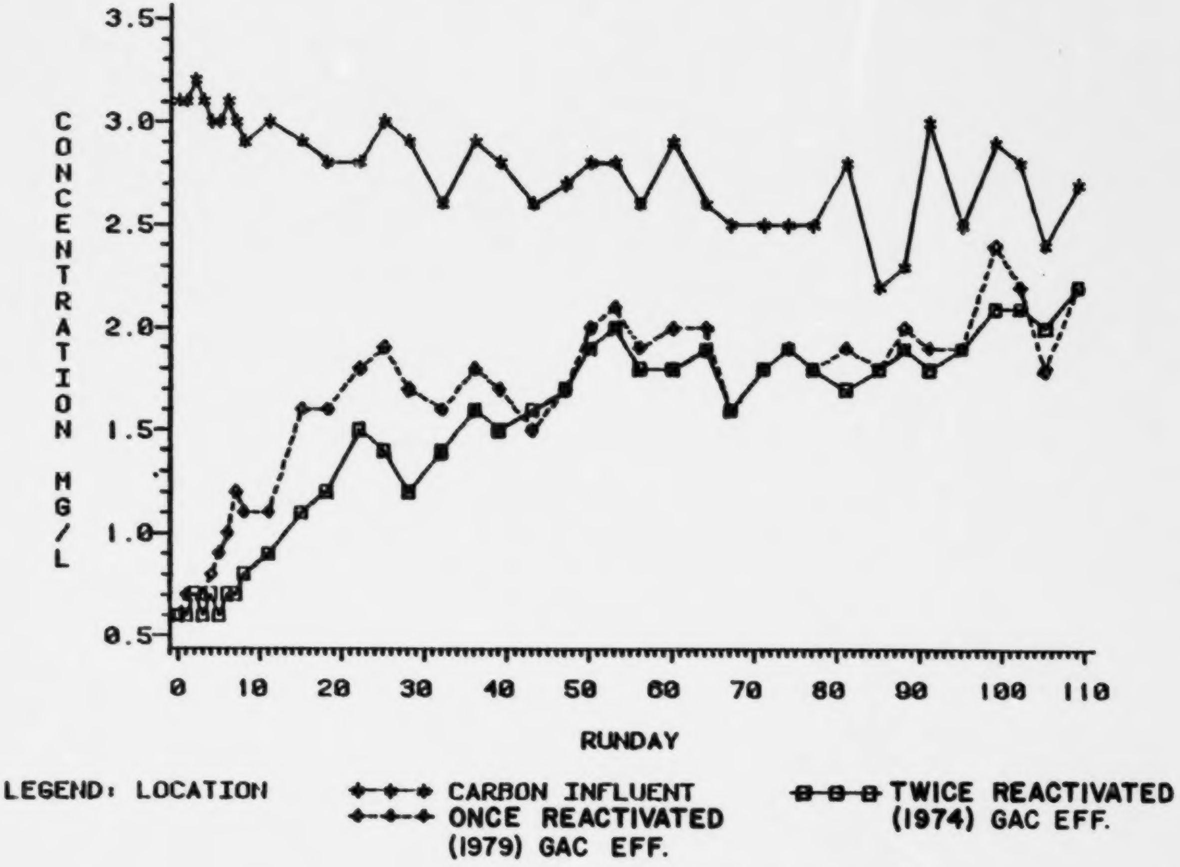


Figure 68. Run 2.—Test filter TOC breakthrough curves.

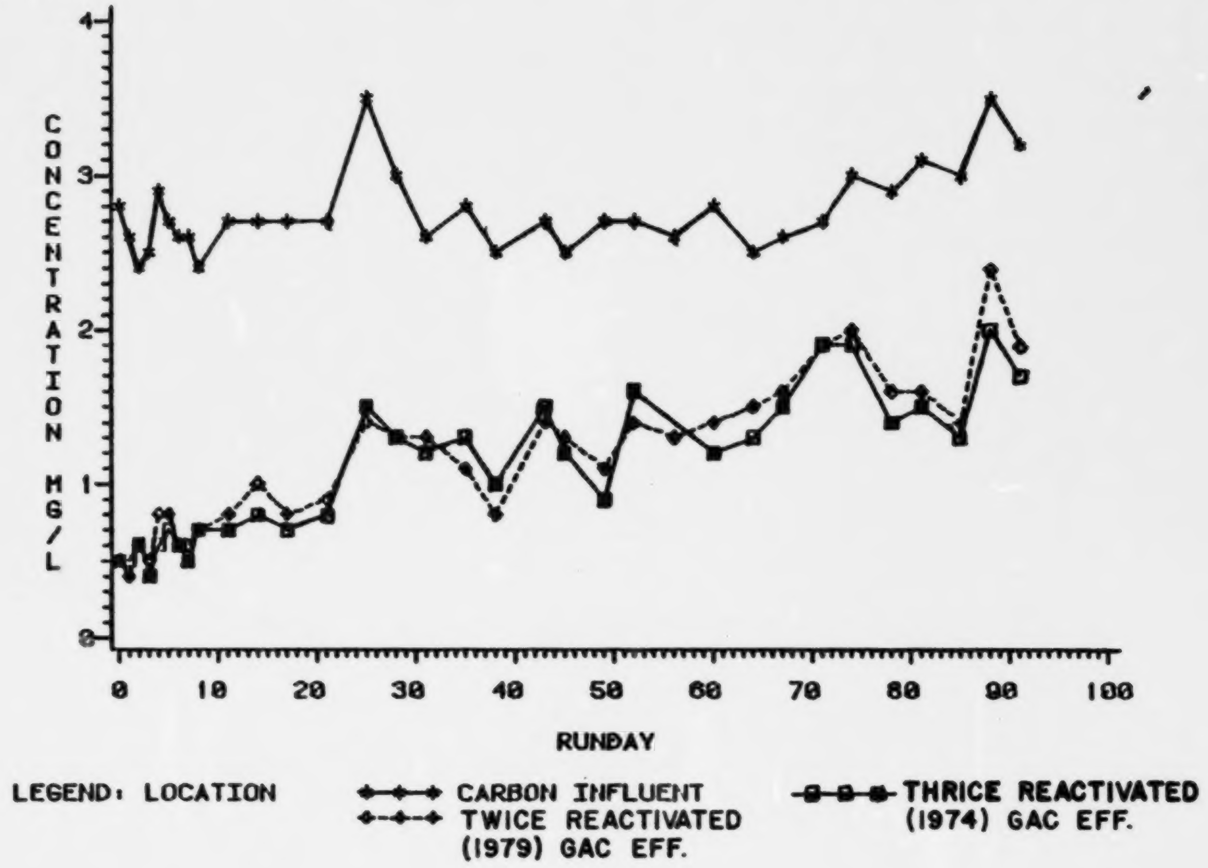


Figure 69. Run 3.—Test filter TOC breakthrough curves.

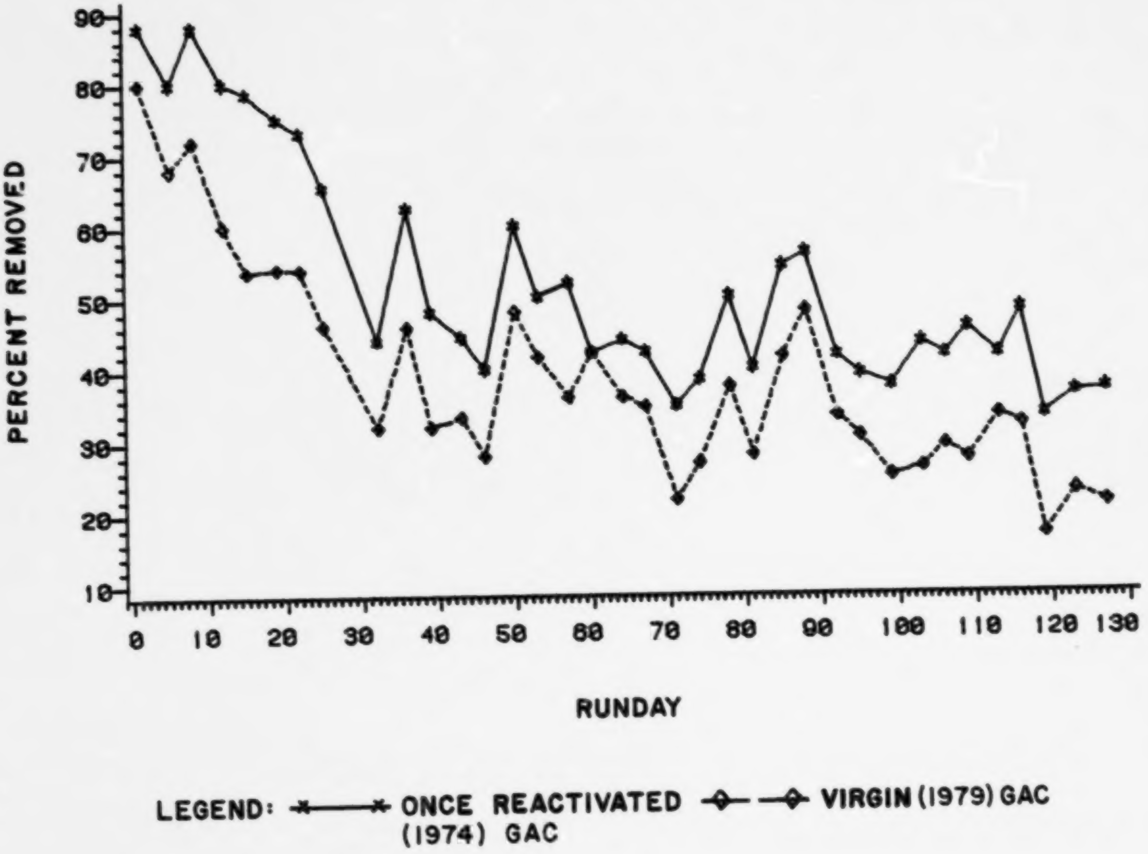


Figure 70. Run I.—Test filter percent removals for TOC.

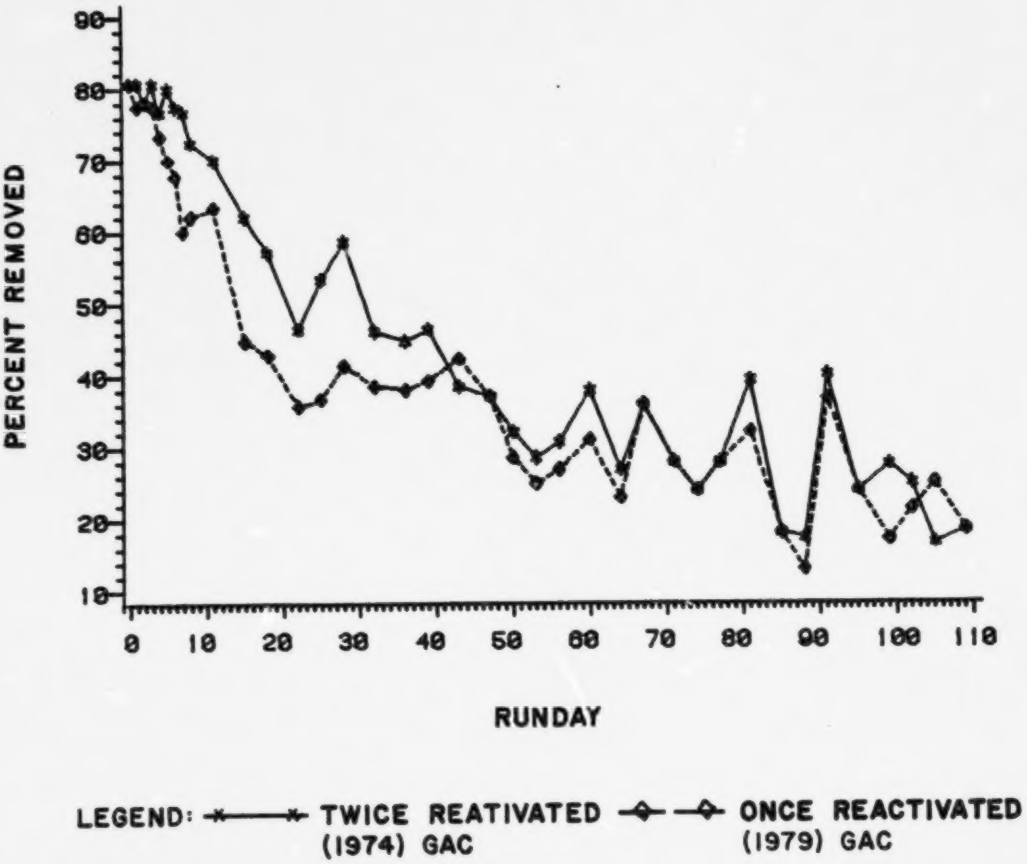


Figure 71. Run 2.—Test filter percent removals for TOC.

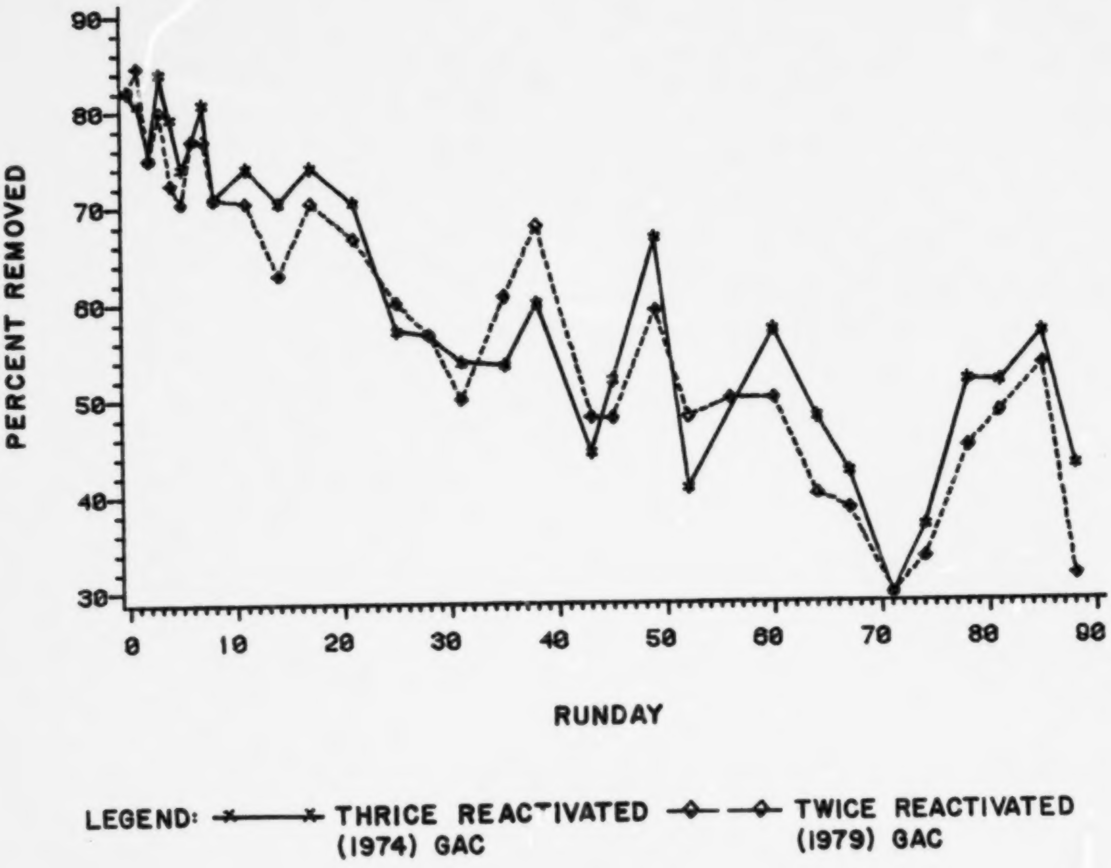


Figure 72. Run 3.— Test filter percent removals for TOC.

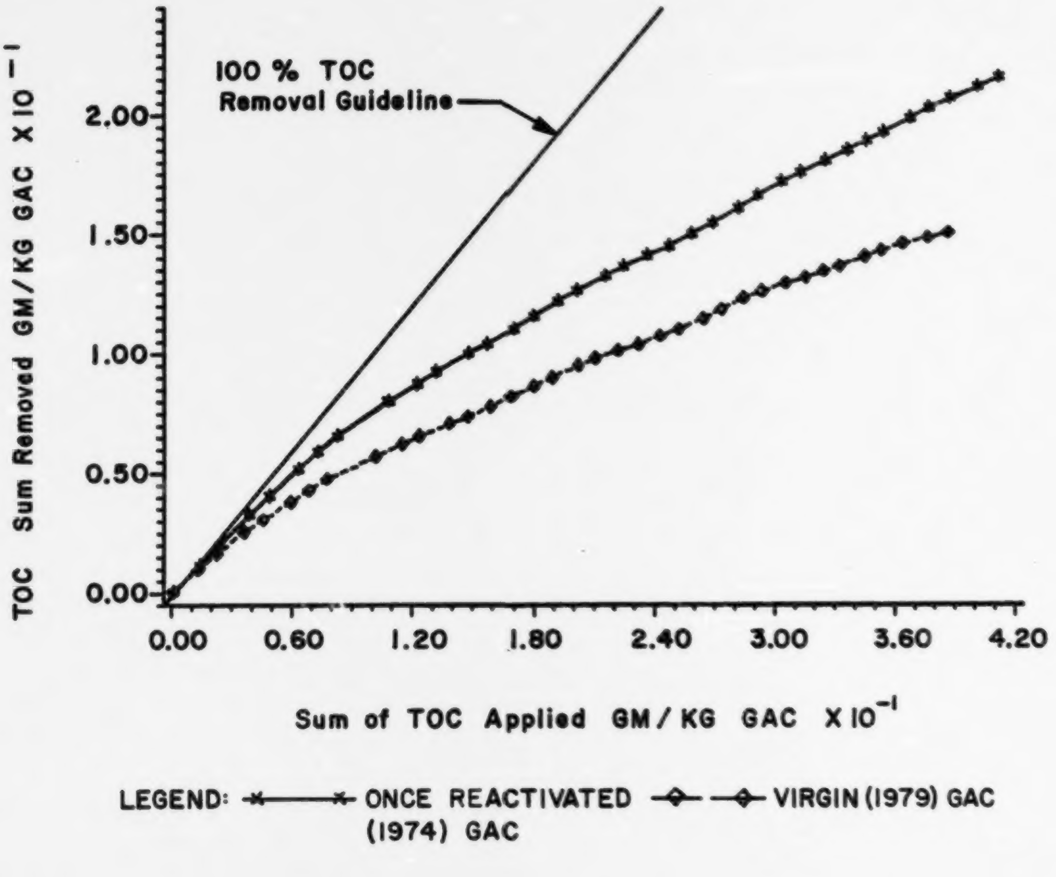


Figure 73. Run I. — Test filter loadings for TOC.

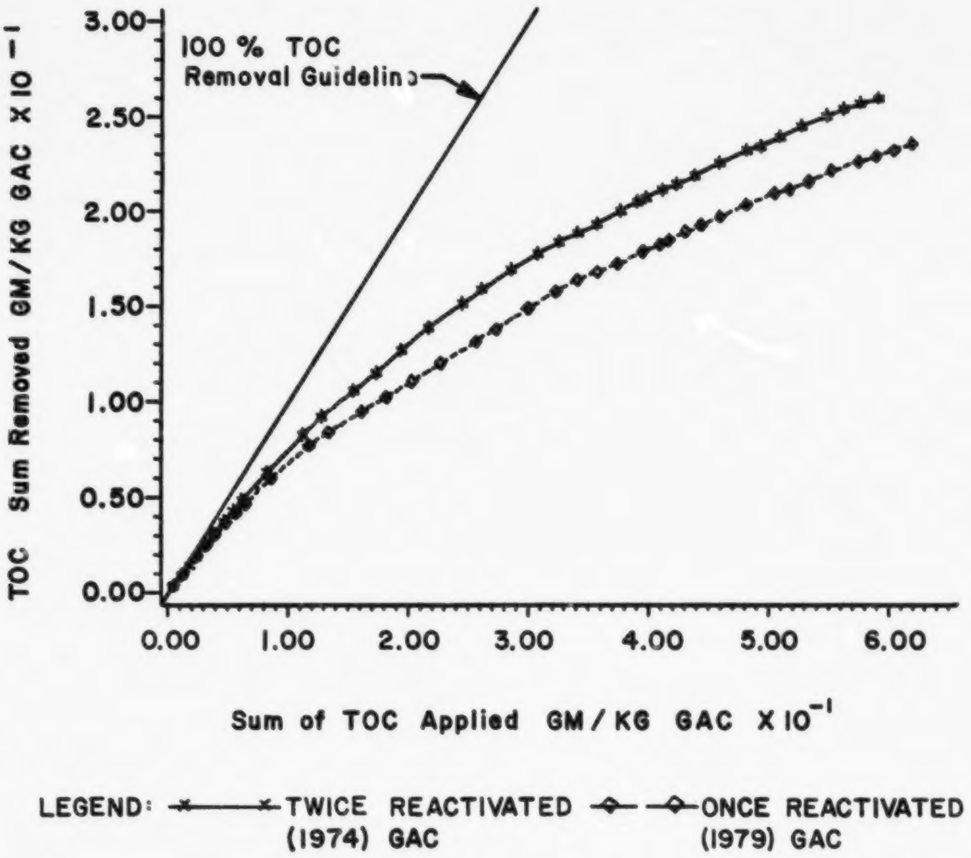


Figure 74. Run 2.—Test filter loadings for TOC.

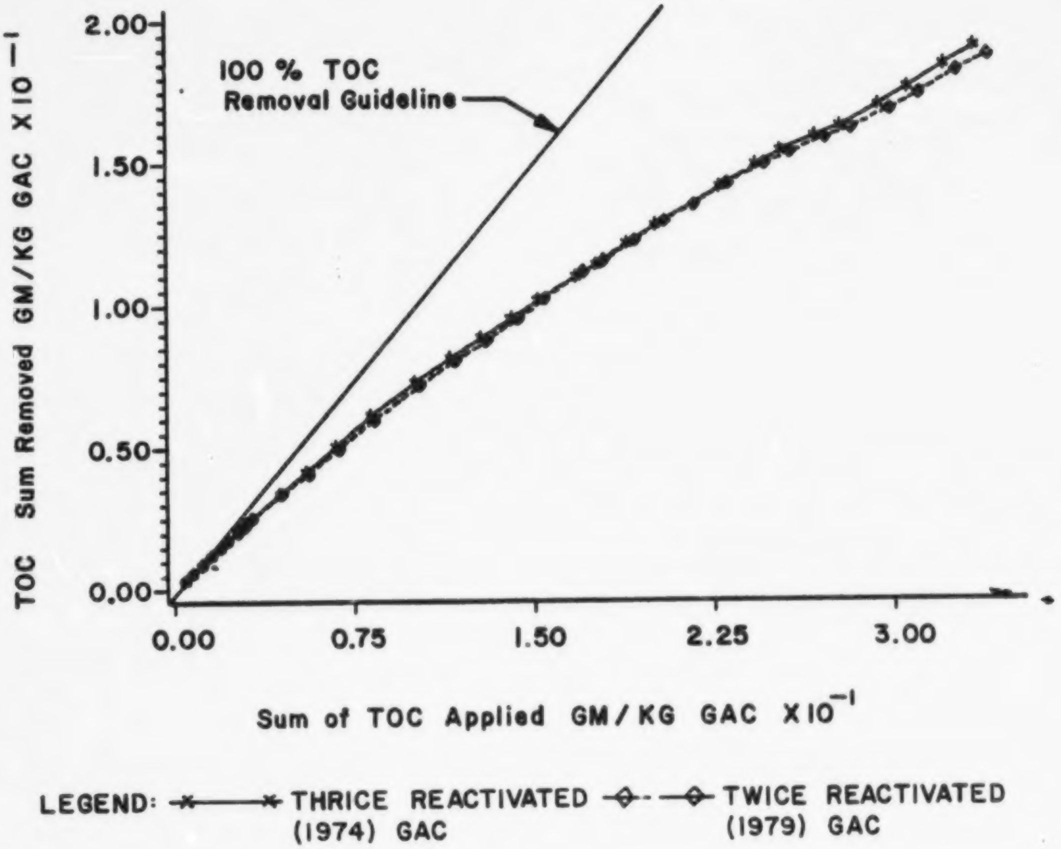


Figure 75. Run 3.—Test filter loadings for TOC.

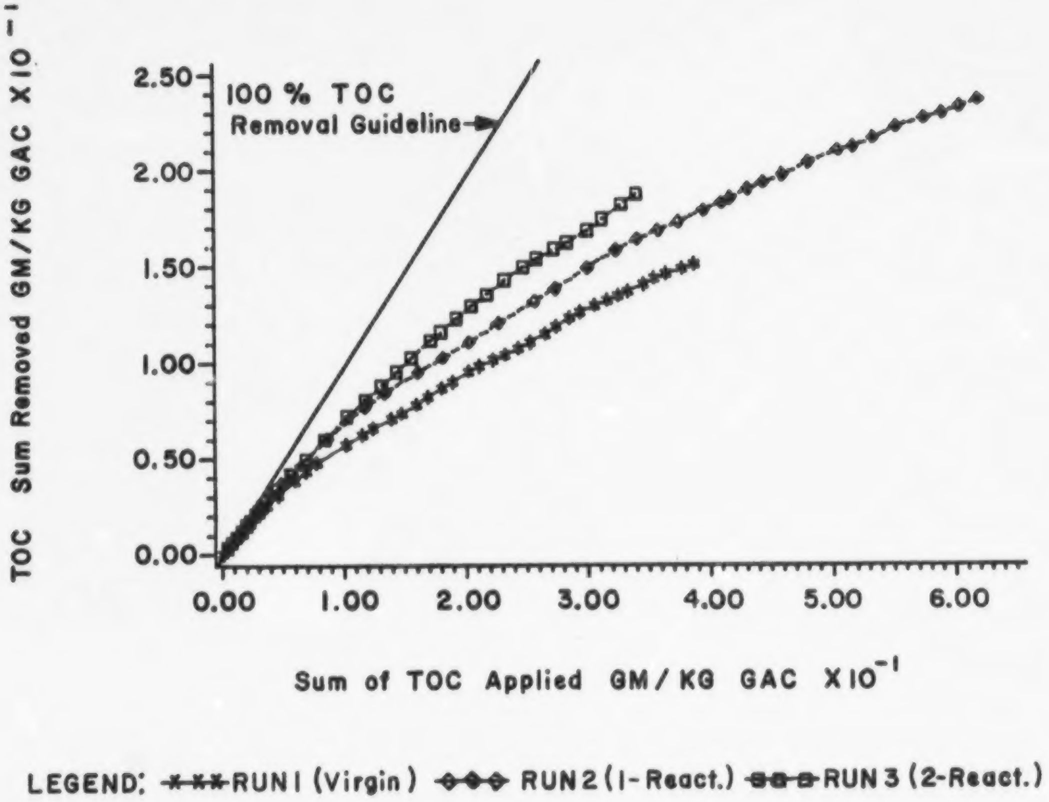


Figure 76. Interun TOC comparison for 1979 (virgin) GAC.

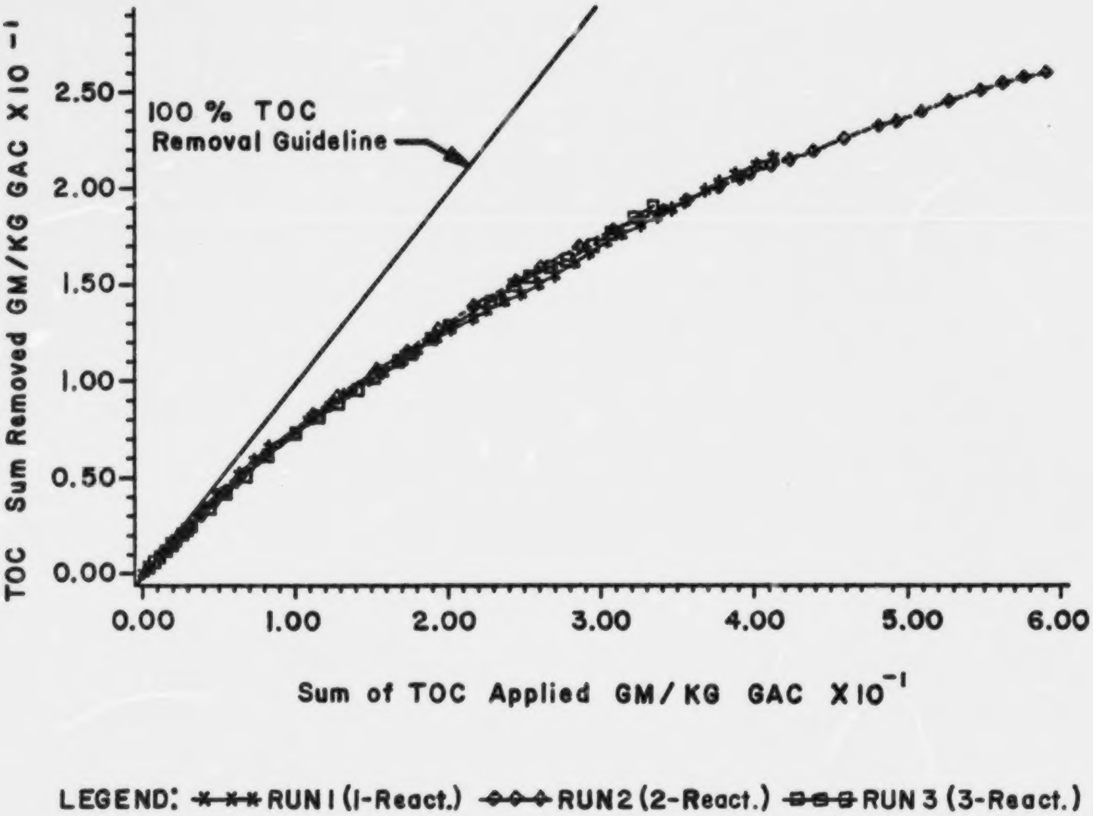


Figure 77. Interun TOC comparison for 1974 (service) GAC.

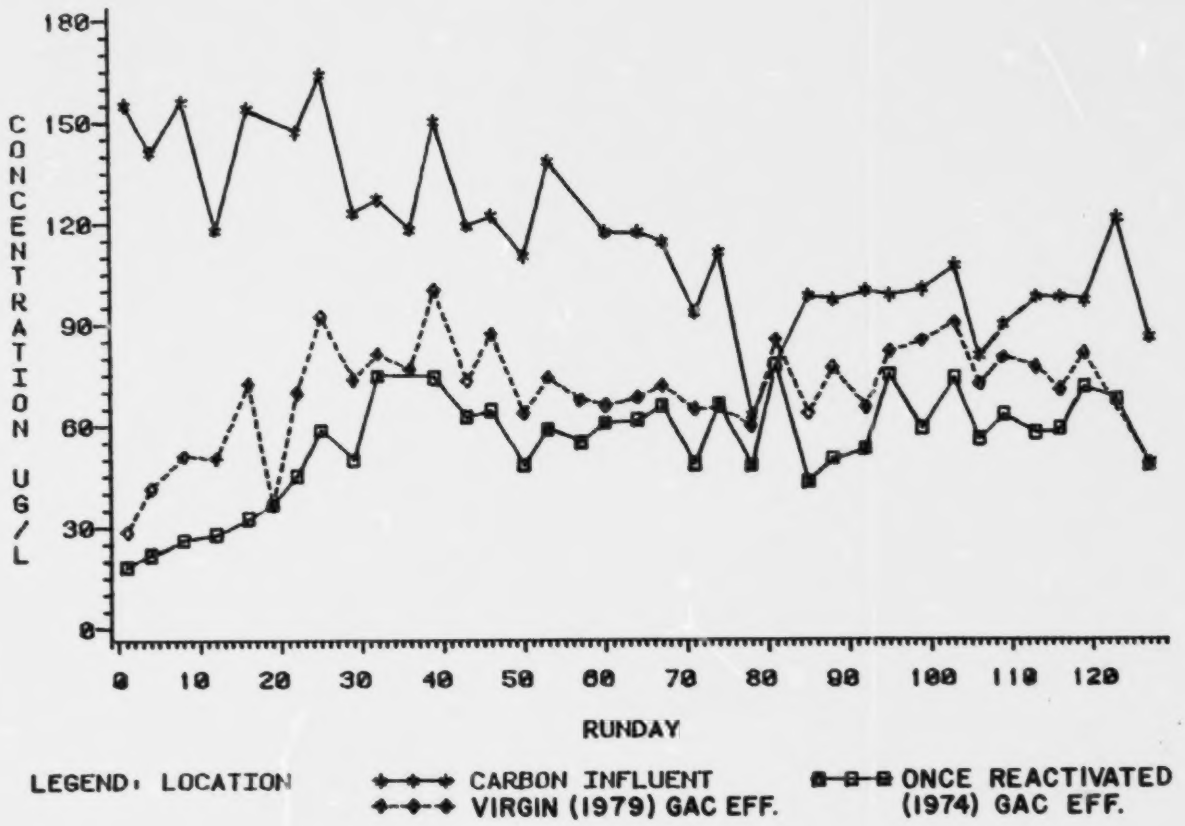


Figure 78. Run I.—Test filter breakthrough curves for three day 28.5°C THMFP.

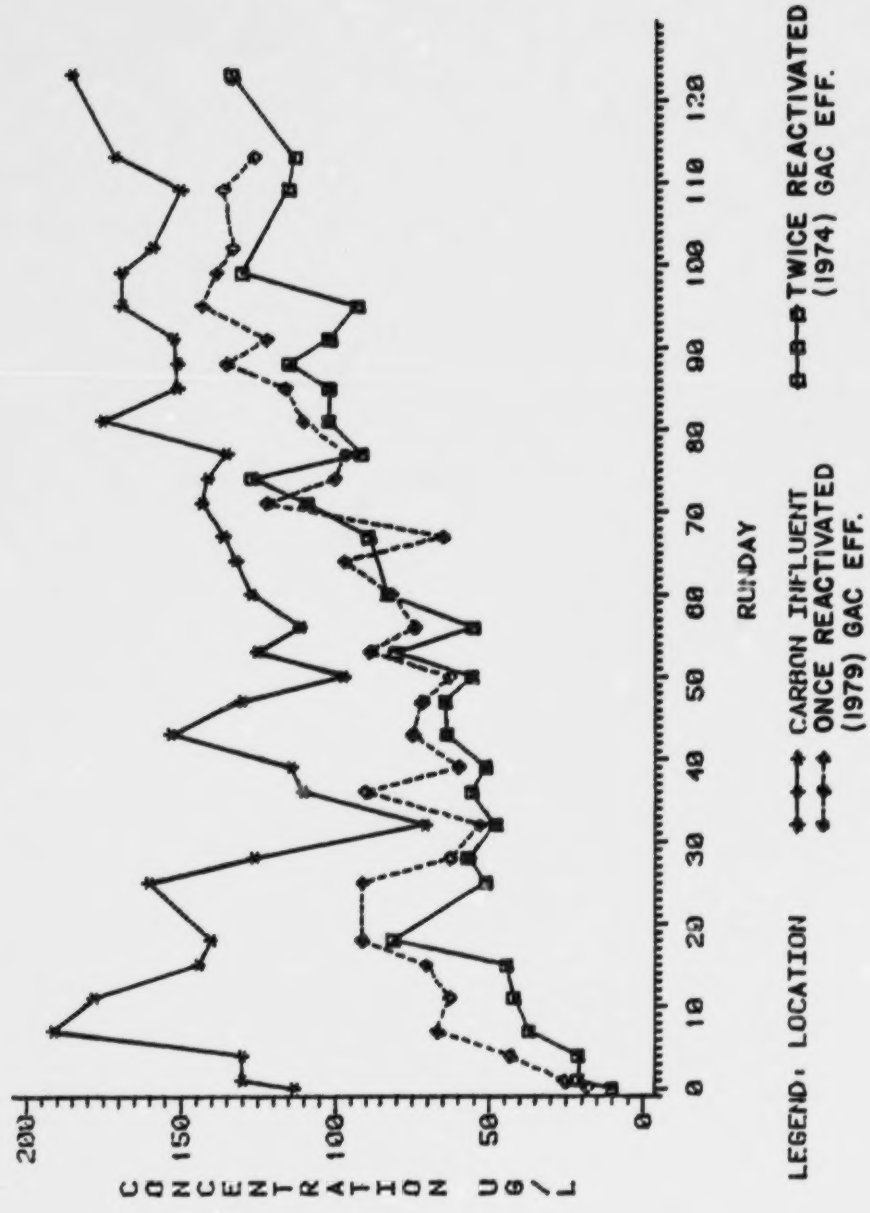


Figure 79. Run 2.—Test filter breakthough curves for three day 28.5°C THMFP.

However, run #3 experienced 7-day maximum THMFP values in the 190 to 250 ug/l range (Figure 91). The 3-day analysis ranged from 30 to 50 ug/l lower (Figure 80) than the 7-day analysis during run #3.

During runs #1 and #3, steady state removal was arrived at after a filter run of about 60 days (Figures 81, 83, 92, and 94). In run #1, the long-term percent removal was on the order of 25% for virgin (1979) GAC and 35% for once reactivated (1974) GAC (Figures 81 and 92). In run #3, following 60 days, the steady state removals were 40% for twice reactivated (1979) GAC and 50% for thrice reactivated (1974) GAC (Figures 82 and 93). This indicates a net increase in THMFP removal performance of approximately 15% at steady state as measured under constant temperature conditions. While the GAC loading curves for THMFP began to coverge with repeated reactivation, their individual characteristics remained more pronounced than for ITHM and TOC (Figures 84 to 86, 95 to 97).

Run #2 THMFP data does not conform to the steady state data for runs #1 and #3. In run #2, steady state was found to occur not until about 90 days into the run (Figures 82 and 93) while runs #1 and #3 achieved steady state in approximately half the time (Figures 81, 83, 92 and 94). However an examination of the loading curves for the GAC during run #2 does indicate that the GAC was adsorbing at a rate in accordance with runs #1 and #3 (Figures 84 - 86 and 95 - 97). The run #2 data demonstrates a relatively low steady state removal percentage which does not conform to the steady state behavior seen in either run #1 or run #3. The 3-day THMFP analyses demonstrated a 10 and 20% removal rate at steady state for once and twice reactivated GAC, respectively (Figure 82). The 7-day THMFP analyses had a steady state removal at 5 and 10% (Figure 93) for once and twice reactivated GAC during run #2. Steady state during runs #1 and #3 for these parameters was over twice this value.

As mentioned previously, average EBCT, loading rates, and ambient temperature conditions for run #2 are the 3 major variables separating run #2 from runs #1 and #3. It was not possible with the data assembled to say which variable, or which combination of variables was responsible for the observed behavior.

No attempt was made to characterize the precursors responsible for THM production in these analyses. Consequently, it is impossible to say whether the nature of the THM precursors seen was consistent or varied widely. It should be noted, however, that the MWW enjoys a very stable and well protected watershed area. The nature of and degree to which the watershed has changed over the past has been primarily under the control of the MWW. As such, any variations in precursors arise as a result of naturally occurring fluctuations in the watershed ecosystem.

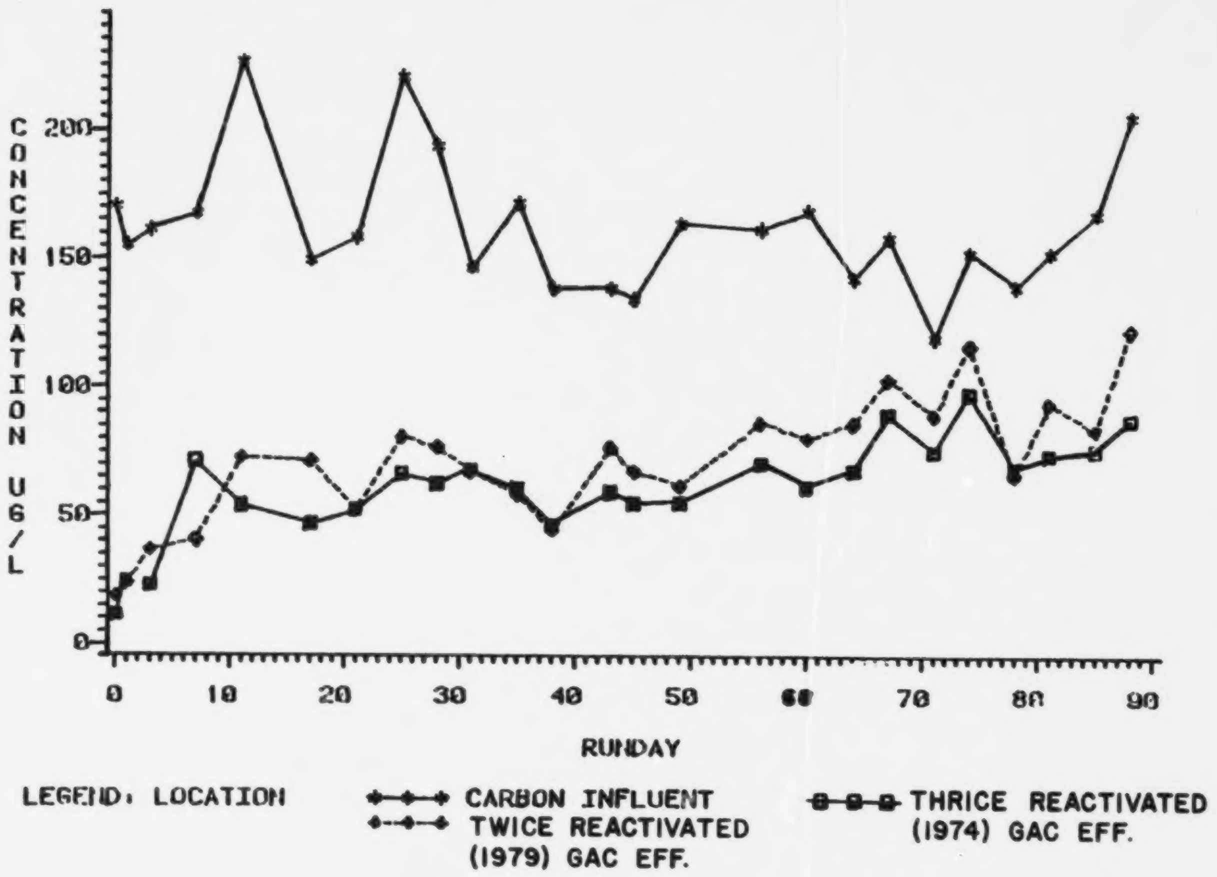


Figure 80. Run 3.—Test filter breakthrough curves for three day 28.5°C THMFP.

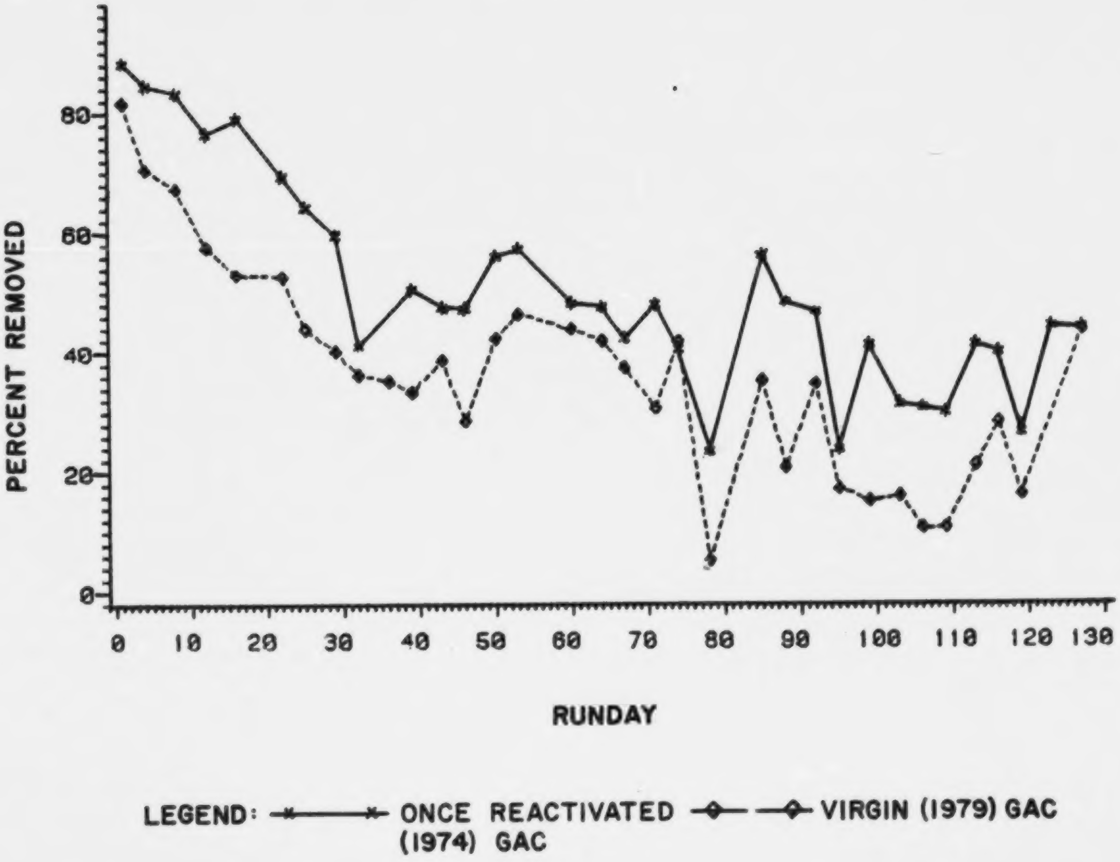


Figure 81. Run 1.— Test filter percent removals for three day 28.5°C THMFP.

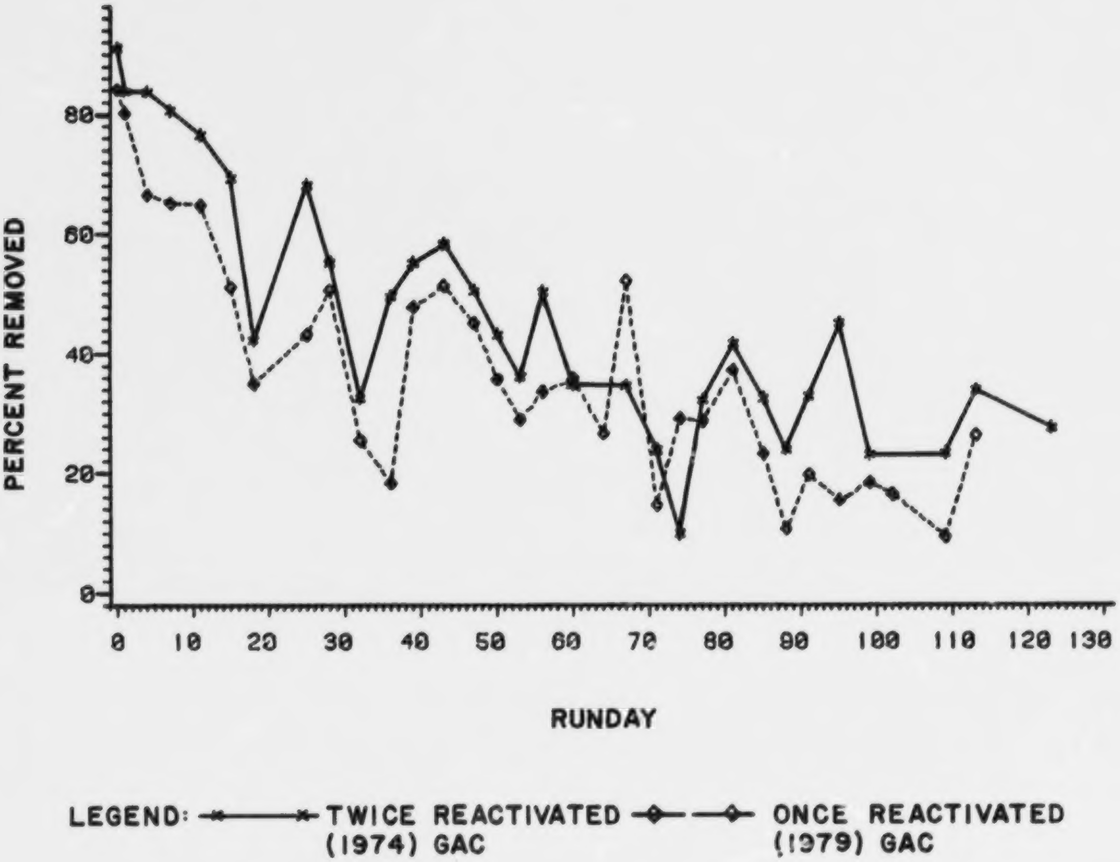


Figure 82. Run 2.—Test filter percent removals for three day 28.5°C THMFP.

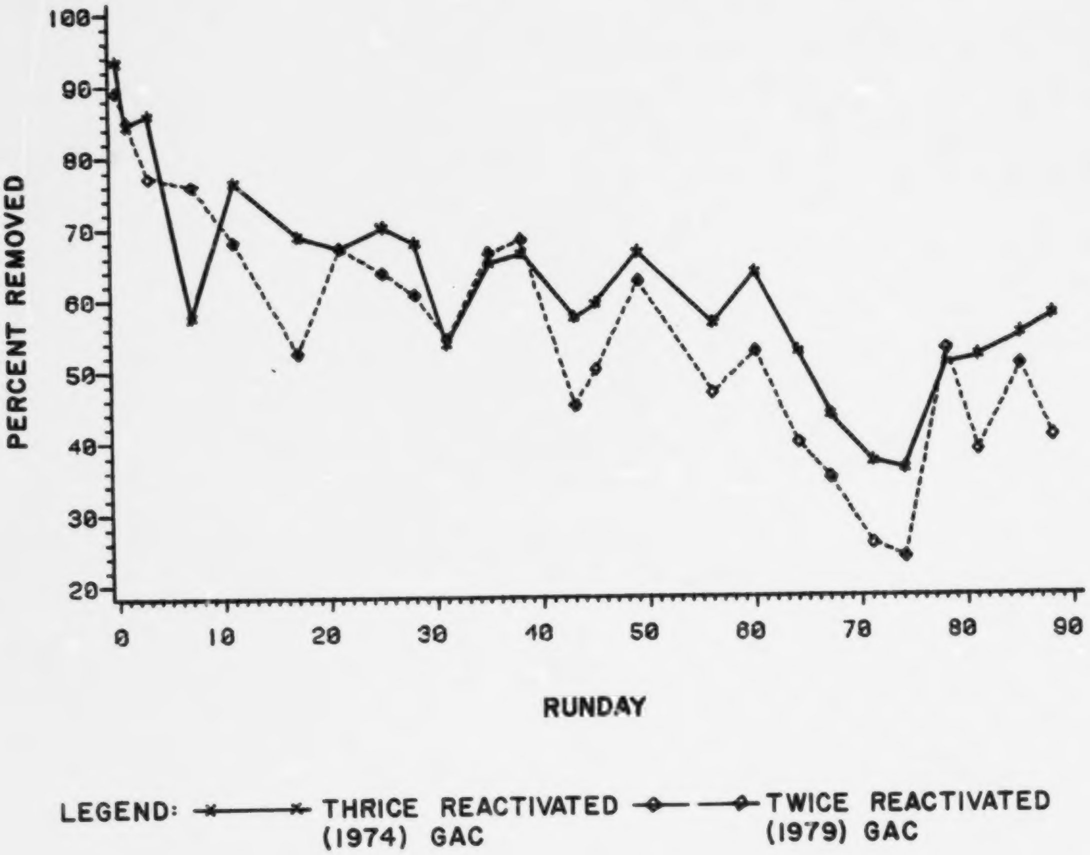


Figure 83. Run 3.— Test filter percent removals for three day 28.5°C THMFP.

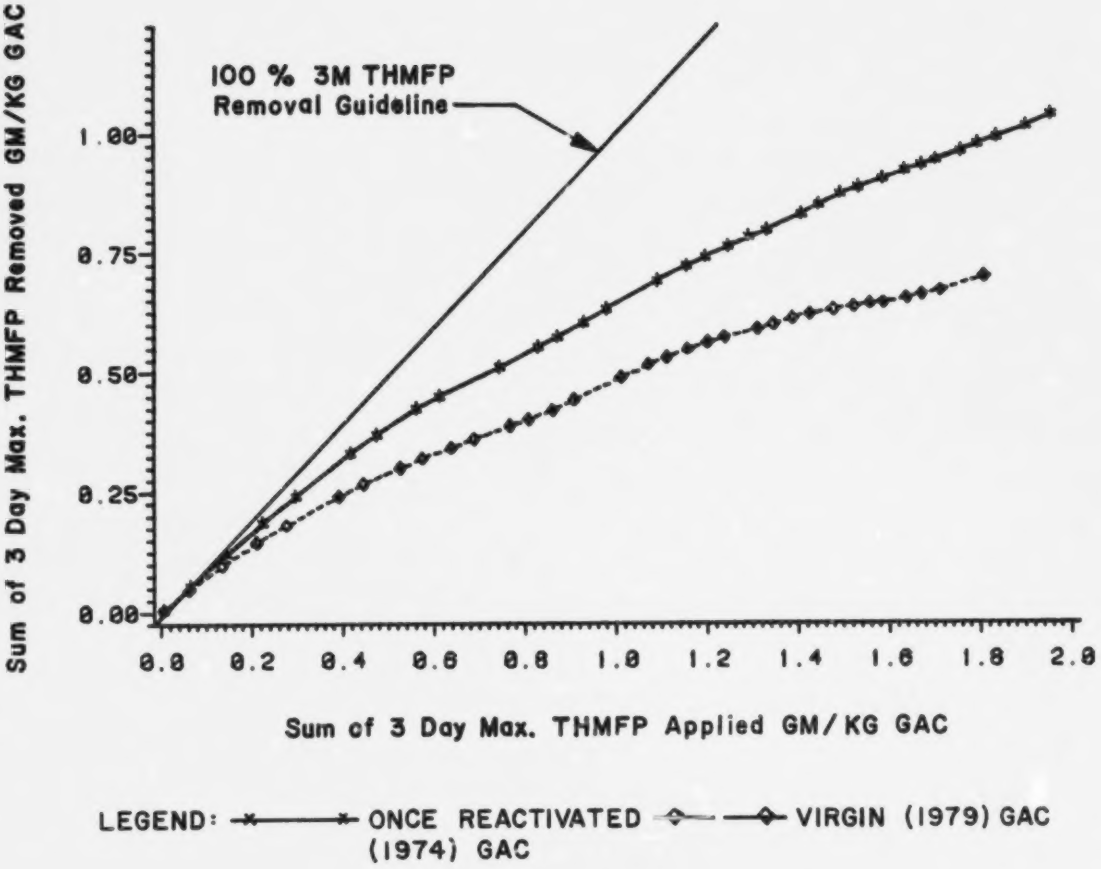


Figure 84. Run I.—Test filter loadings for three day 28.5°C THMFP.

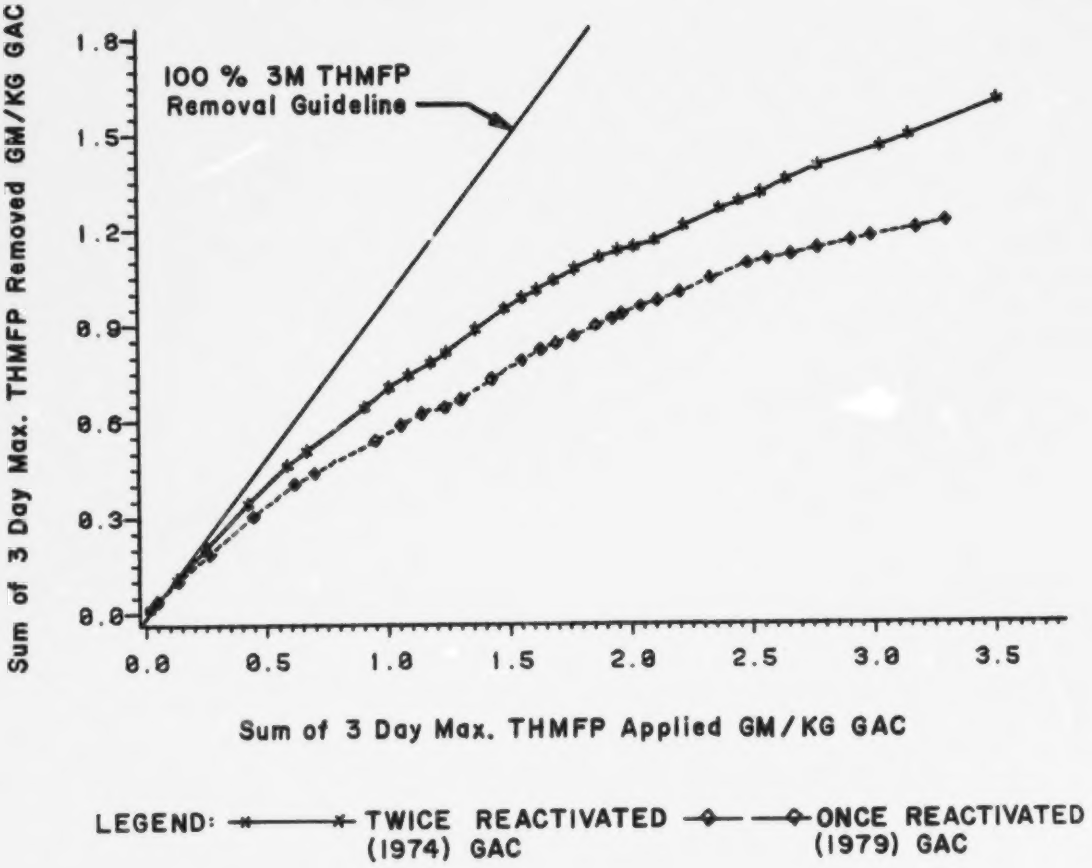


Figure 85. Run 2.— Test filter loadings for three day 28.5°C THMFP.

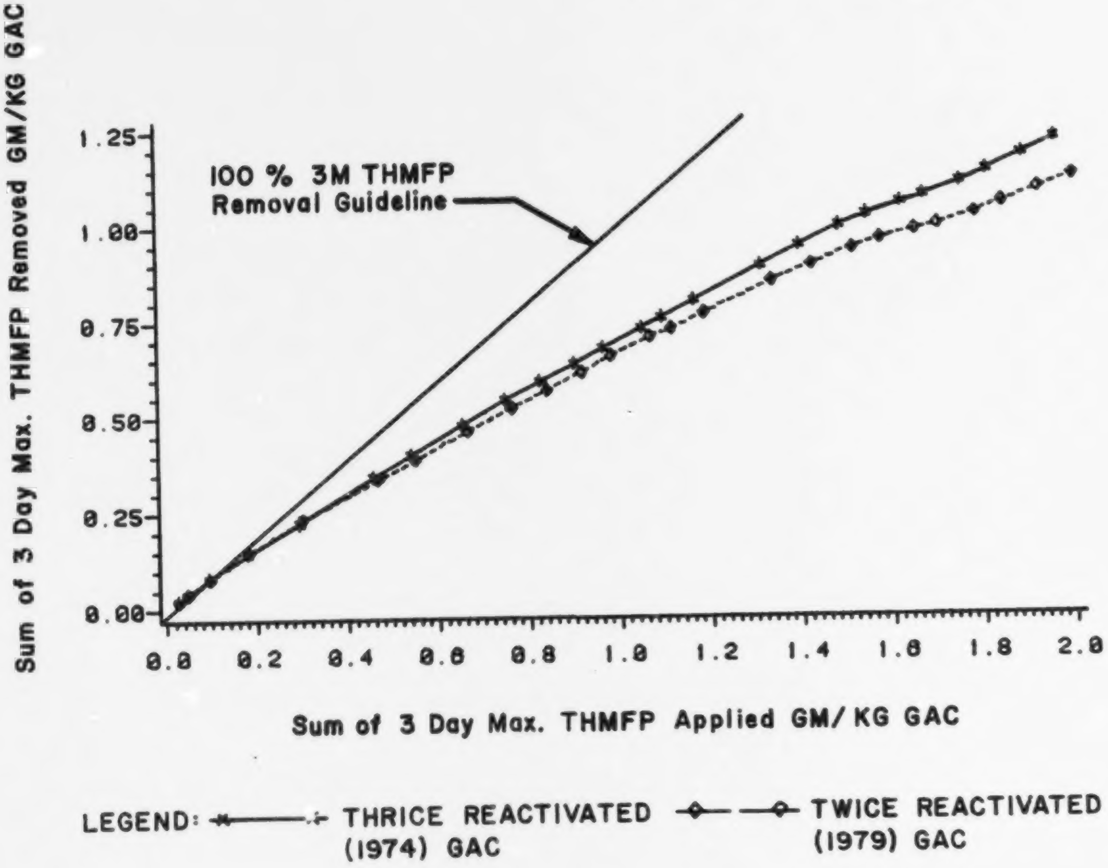


Figure 86. Run 3.—Test filter loadings for three day 28.5°C THMFP

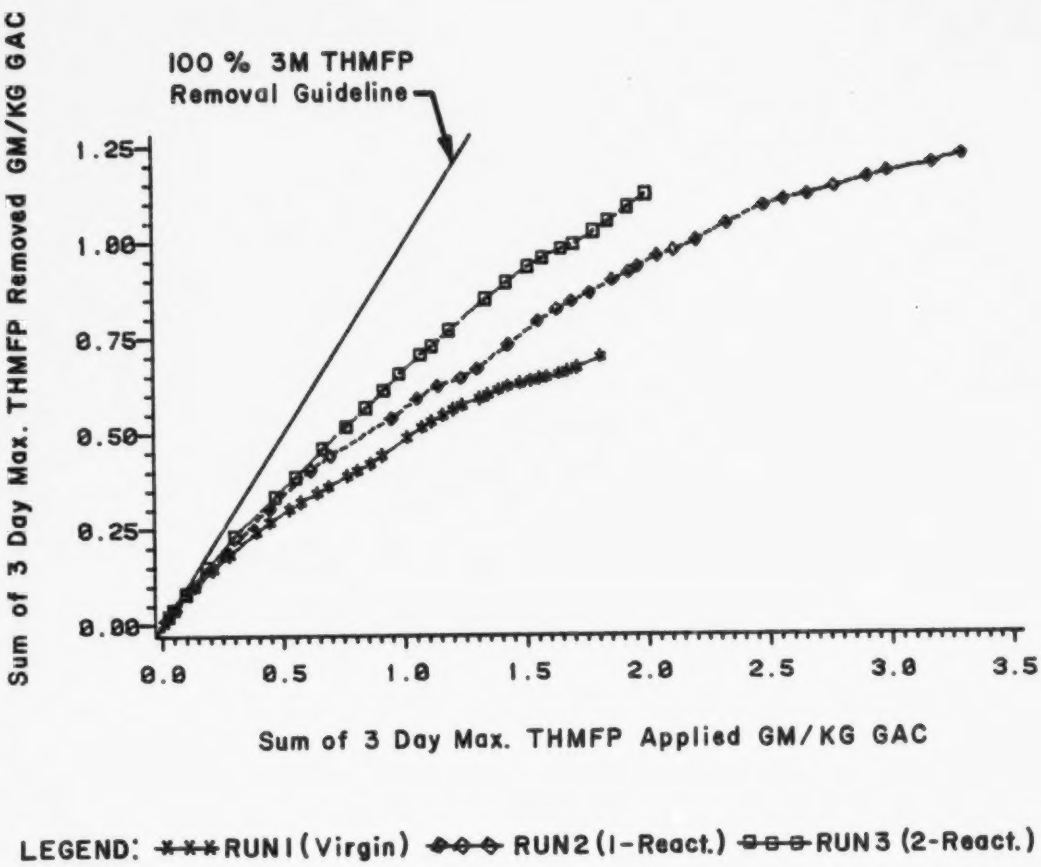


Figure 87. Interun 3 day max. THMFP comparison for 1979 (virgin) GAC.

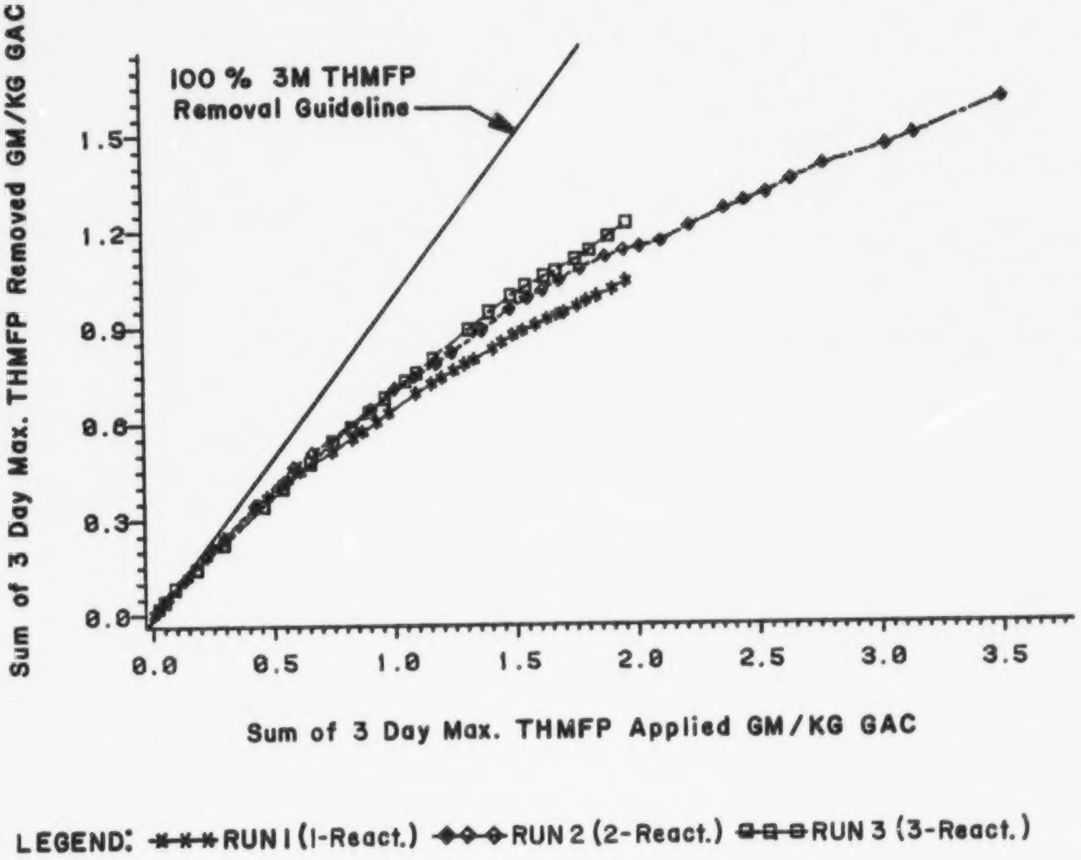


Figure 88. Interun 3 day max. THMFP comparison for 1974 (service) GAC.

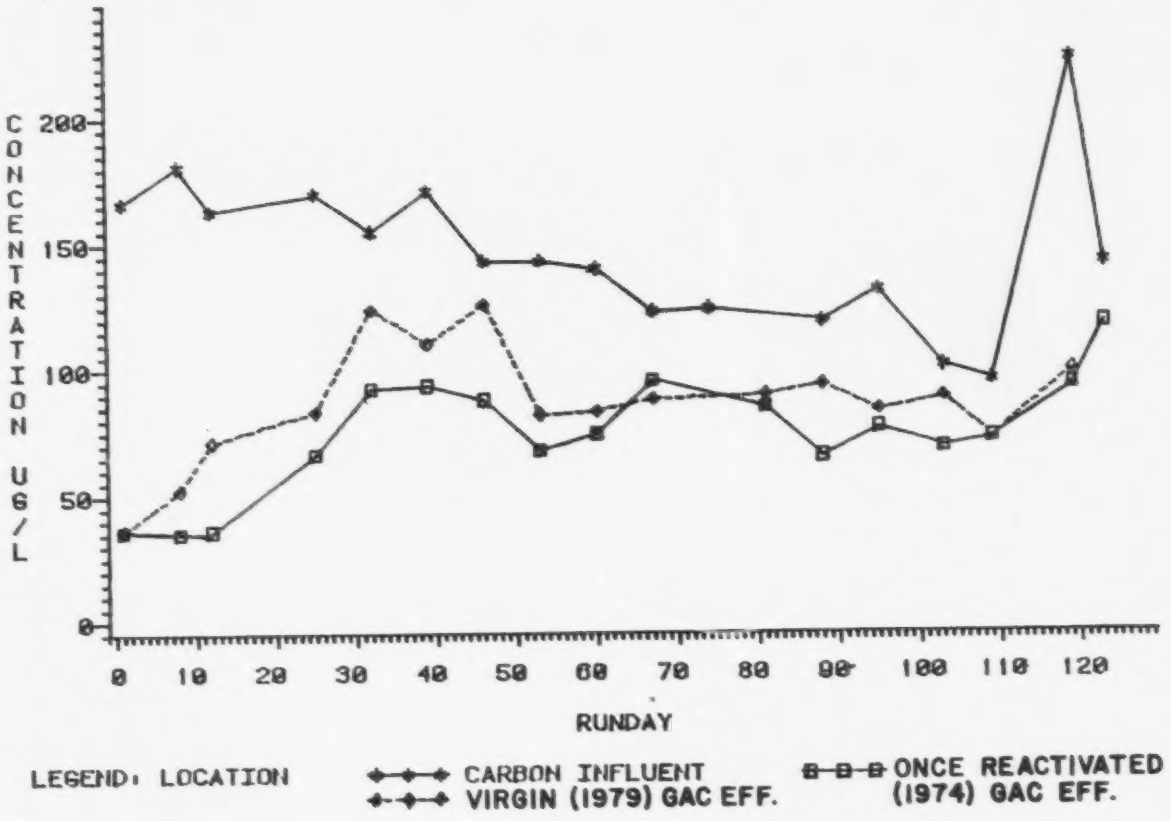


Figure 89. Run I.—Test filter breakthrough curves for seven day 28.5°C THMFP.

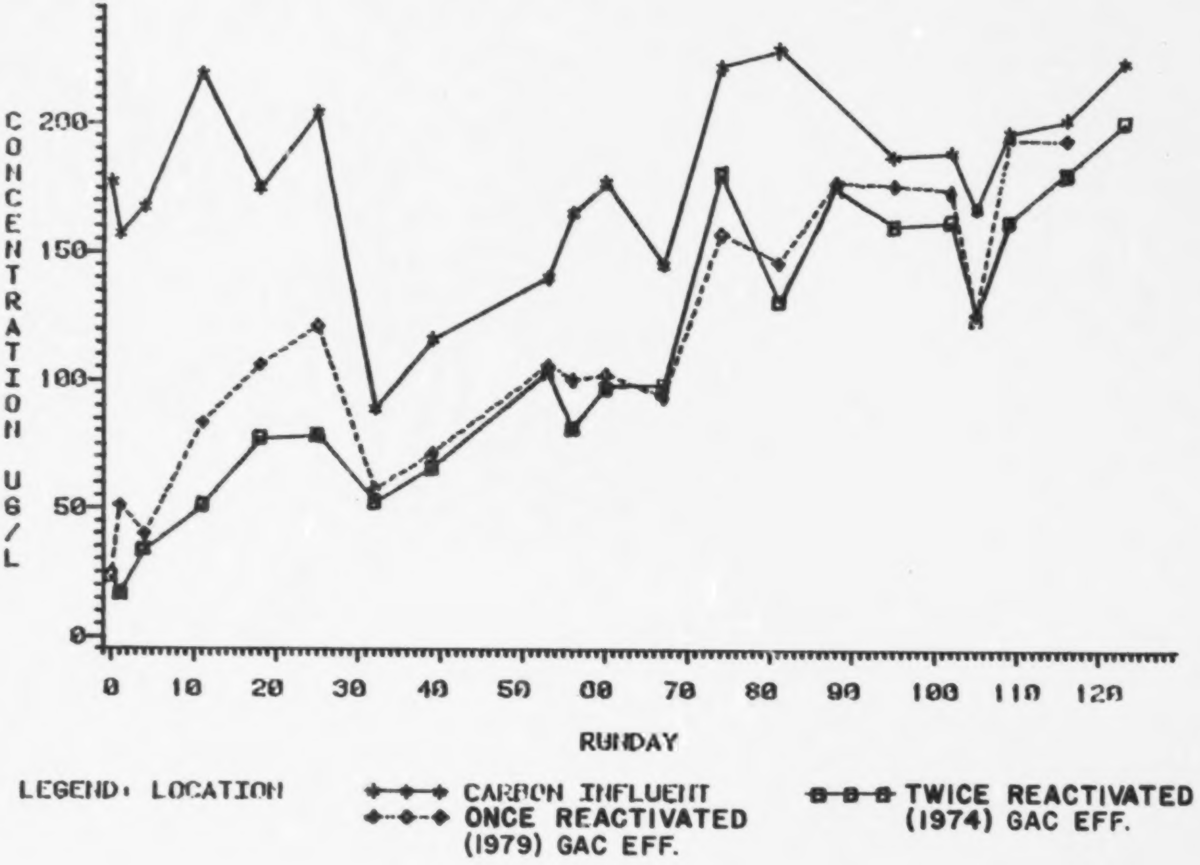


Figure 90. Run 2.—Test filter breakthrough curves for seven day 28.5°C THMFP.

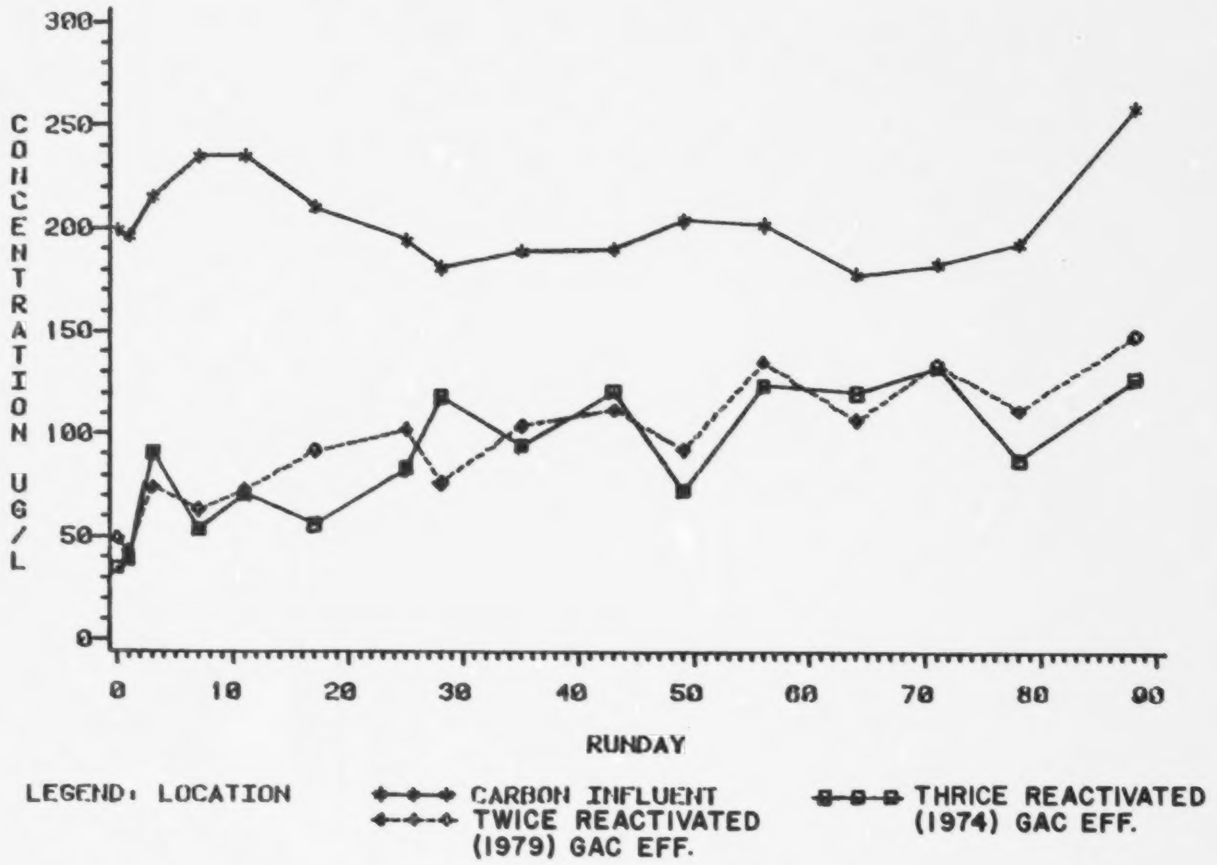


Figure 91. Run 3.— Test filter breakthrough curves for seven day 28.5°C THMFP.

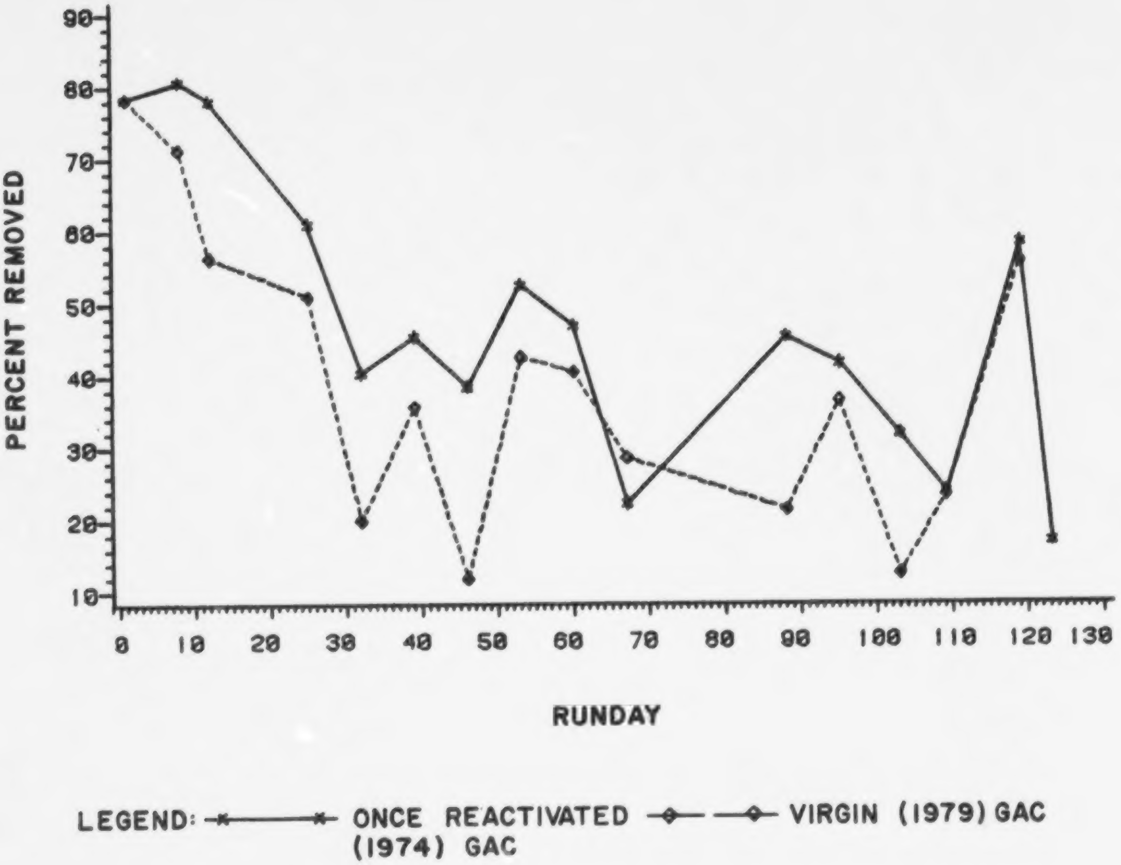


Figure 92. Run I.—Test filter percent removals for seven day 28.5°C THMFP.

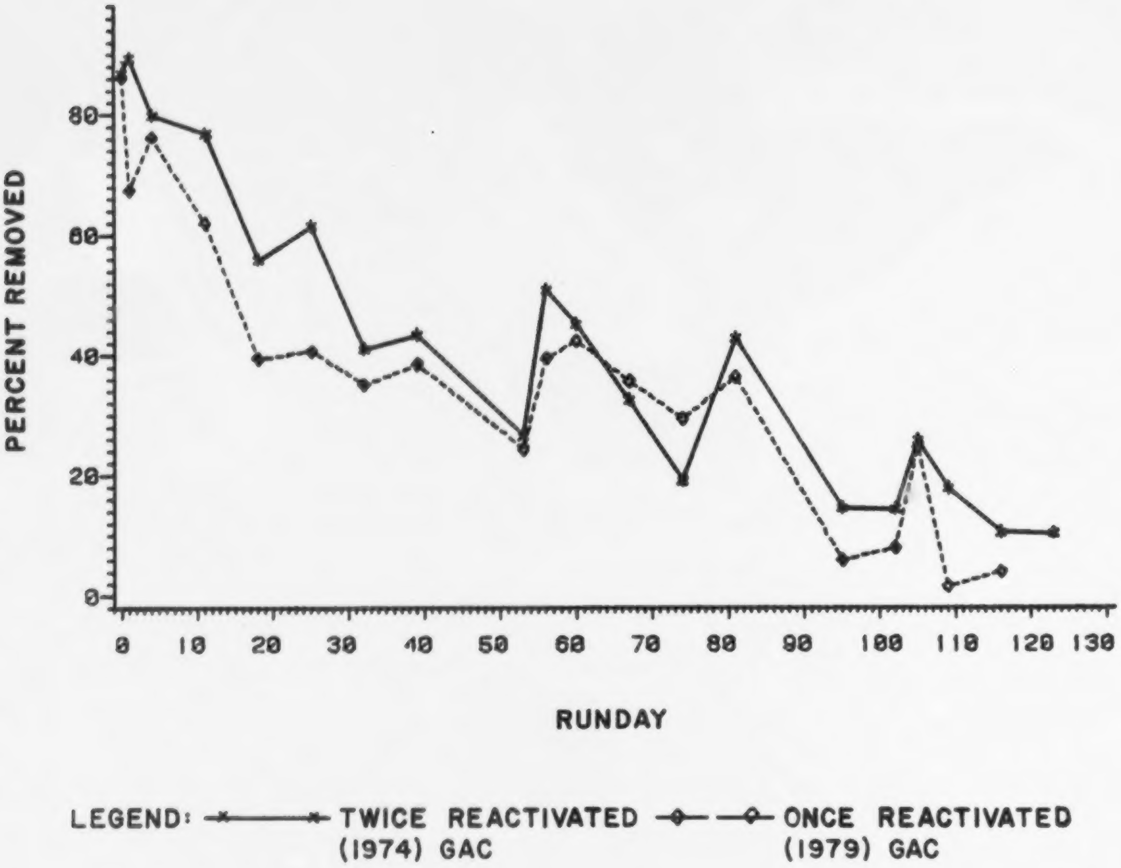


Figure 93. Run 2.—Test filter percent removals for seven day 28.5°C THMFP.

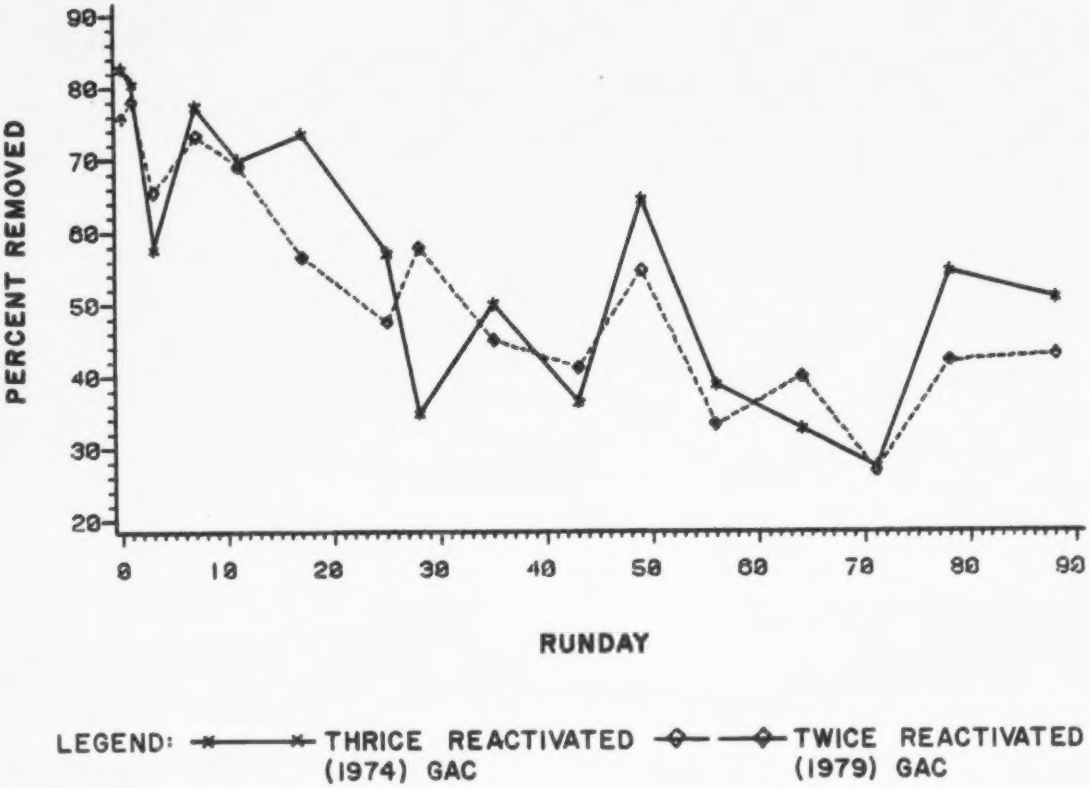


Figure 94. Run 3.— Test filter percent removals for seven day 28.5°C THMFP.

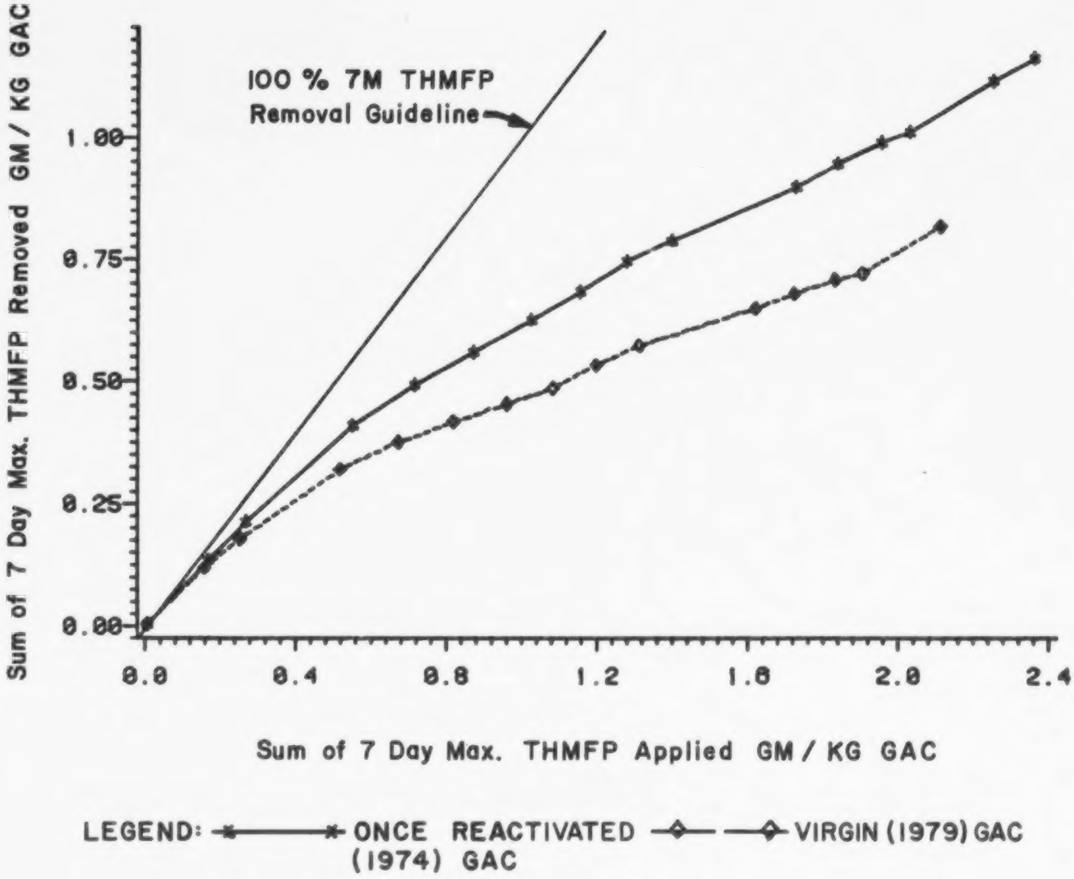


Figure 95. Run I.—Test filter loadings for seven day 28.5°C THMFP.

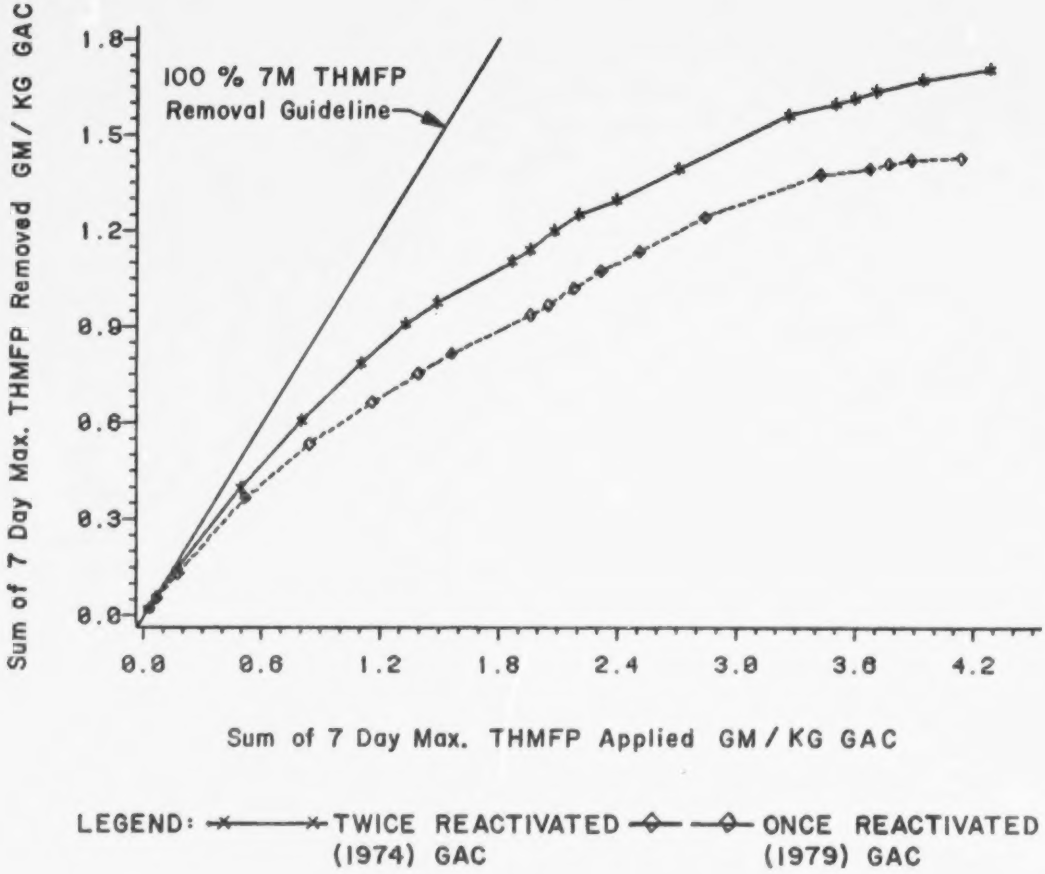


Figure 96. Run 2.— Test filter loadings for seven day 28.5°C THMFP.

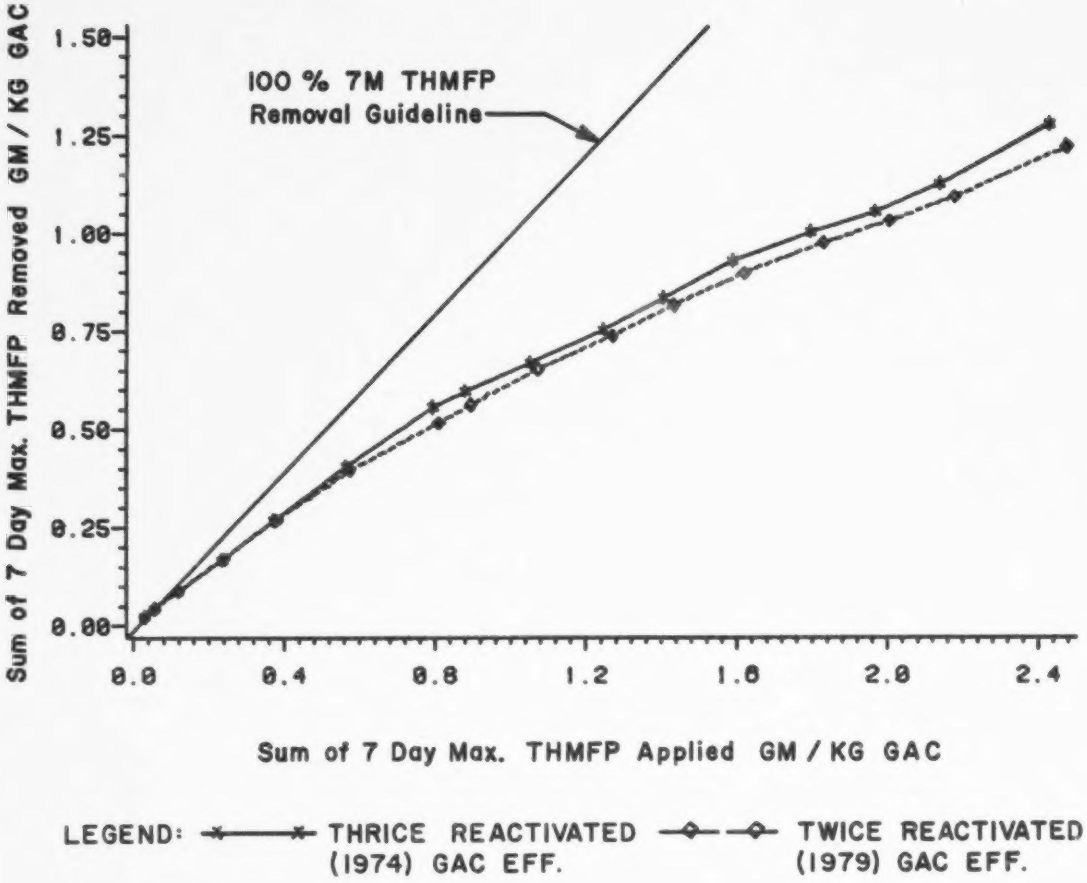


Figure 97. Run 3. — Test filter loadings for seven day 28.5°C THMFP.

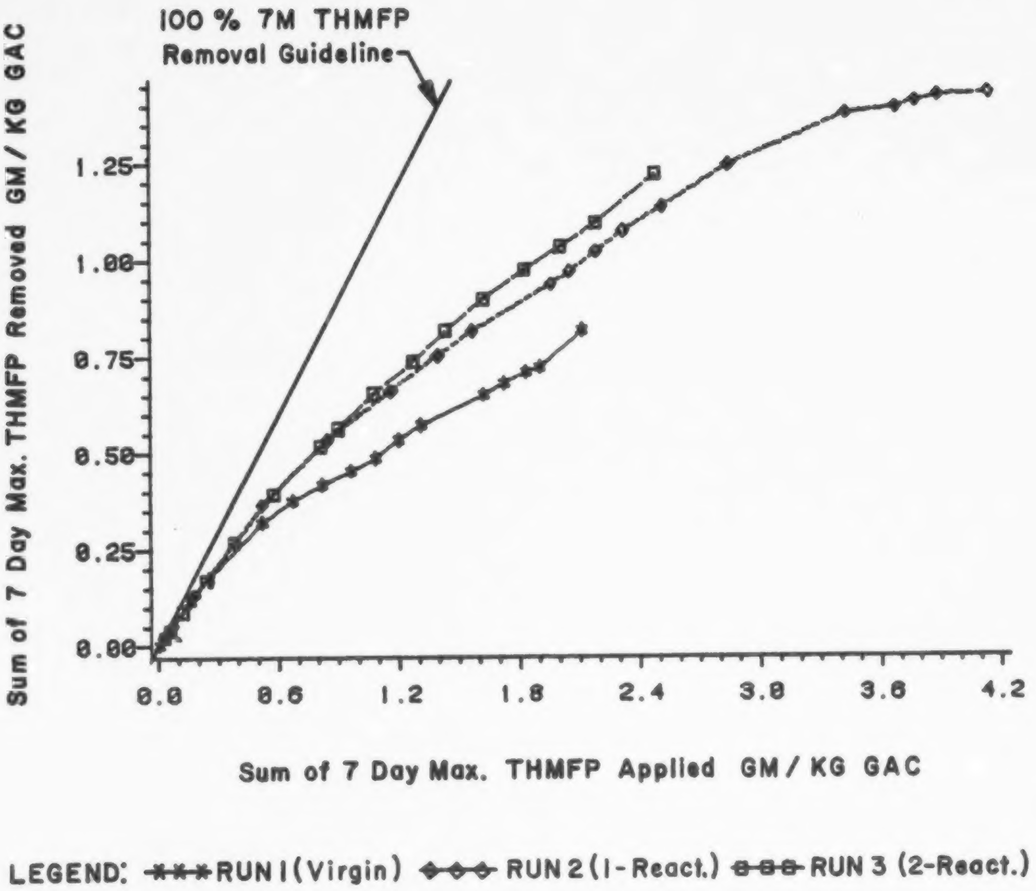


Figure 98. Interun 7 day max. THMFP comparison for 1979 (virgin) GAC.

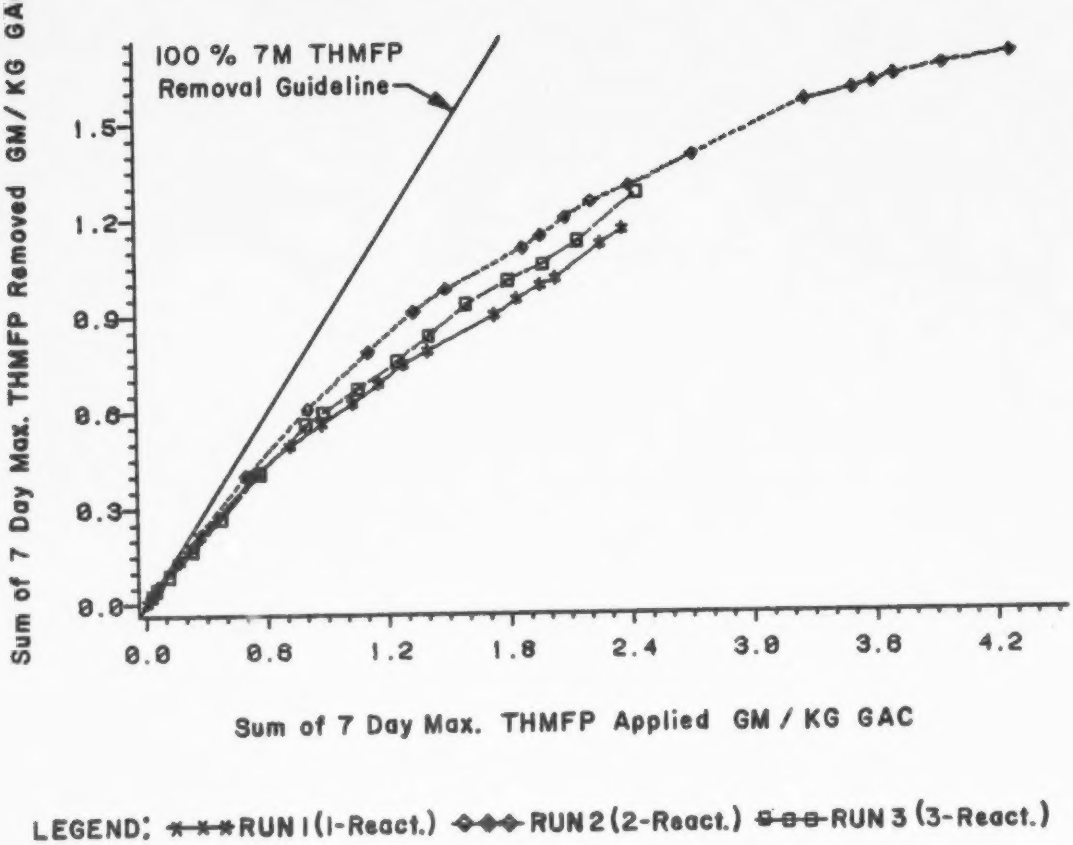


Figure 99. Interun 7 day max. THMFP comparison for 1974 1974 (service) GAC.

Regardless of precursors, etc., the pattern towards convergence of the loading curves with repeated reactivation for the 2 medias was observed. Also, under similar temperature, EBCT and loading rate conditions (run #1 and run #3), a general trend was observed towards improved removal performance as a function of subsequent reactivation cycles.

Color, Turbidity, Bacteriological and pH

Analyses for apparent color, turbidity, bacteriological activity and pH constituted the remainder of the test filter water quality monitoring program. These parameters are frequently and routinely monitored at the Manchester WTP.

Apparent color and turbidity reduction through the test filter was found to be identical for each media during each filter run. Average apparent color applied was 2 units, and the average color in the effluent was 1 unit. Likewise, turbidities on the order of 0.2 NTU were applied and the effluents were routinely very similar and on the order of 0.1 NTU. Because of the small reductions and inherent lack of precision in these analyses, no attempt was made to establish a correlation between them and TOC or THMFP.

Positive SPC and TC analyses of the test filter effluents were found to be minimal. Although run #1 and run #3 had essentially no positives for these analyses, run #2 did produce some positive results (Figures 100 and 101). The frequency and number of positives decreased as run #2 progressed. Ambient water temperature during run #2 followed the same pattern, providing evidence of a correlation (Figure 52).

pH alteration in the freshly reactivated GAC beds produced a pattern of initial elevation followed by late run suppression (Figures 102, 103 and 104). The virgin GAC effluent, however, did not demonstate the magnitude of initial pH elevation seen in the reactivated media effluents (Figure 102). While the virgin GAC exhibited very little initial pH elevation, the pH value for once reactivated GAC in run #1 (Figure 102) was increased by about 1.2 units for approximately 10 days. However, in runs #2 and #3, this increase was more pronounced at 2.5 to 3 pH units (Figures 103 and 104). The duration of the increase was just under 10 run days. pH suppression in runs #1 and #3 averaged 0.2 units and did not develop to a noticeable extent until 60 run days. Run #2 demonstrated no measureable pH suppression, perhaps, as a result of EBCT, temperature or the nature of the adsorbate involved.

GAC Analyses

Laboratory GAC characterizations were made during this research by the MWW, the Georgia Tech Experiment Station, and by

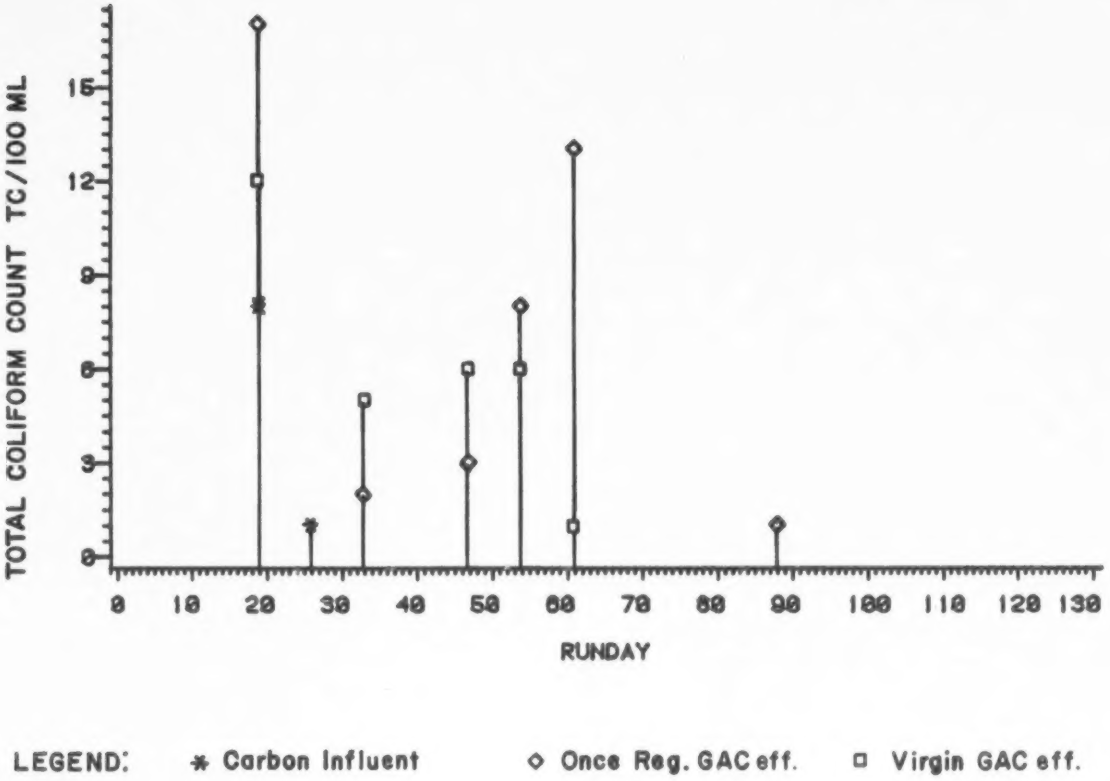


Figure 100. Run 2.– Test filter total coliform.

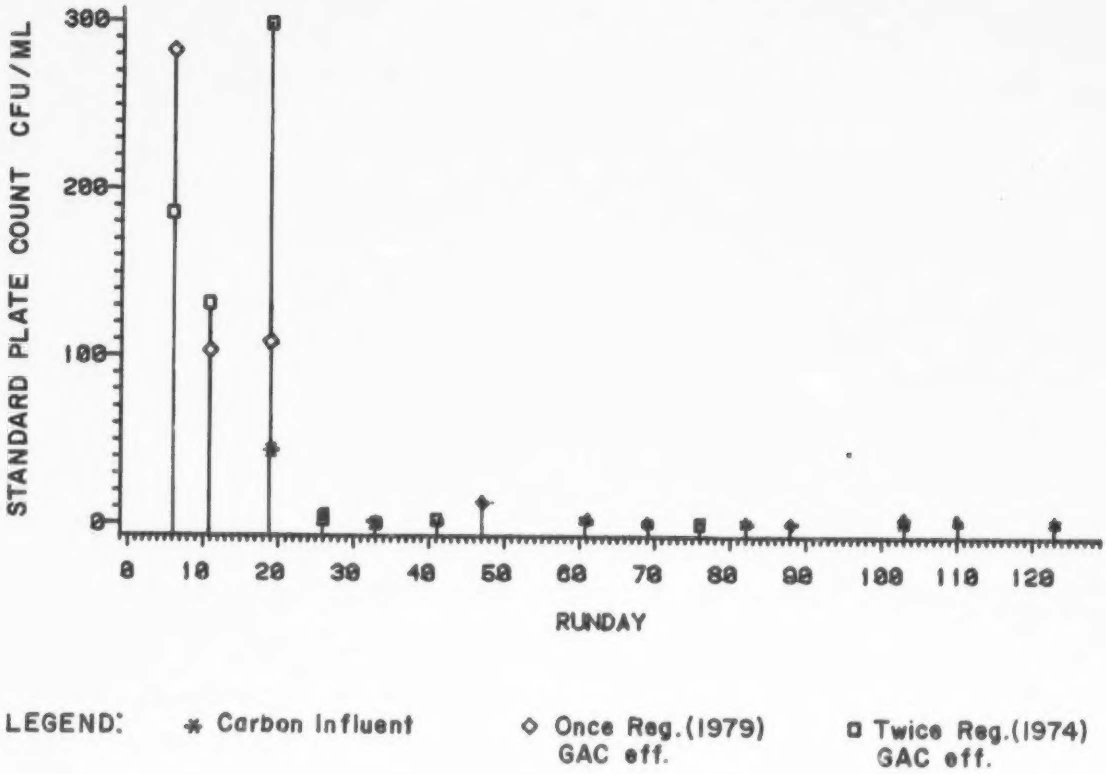


Figure 101. Run 2.– Test filter standard plate count.

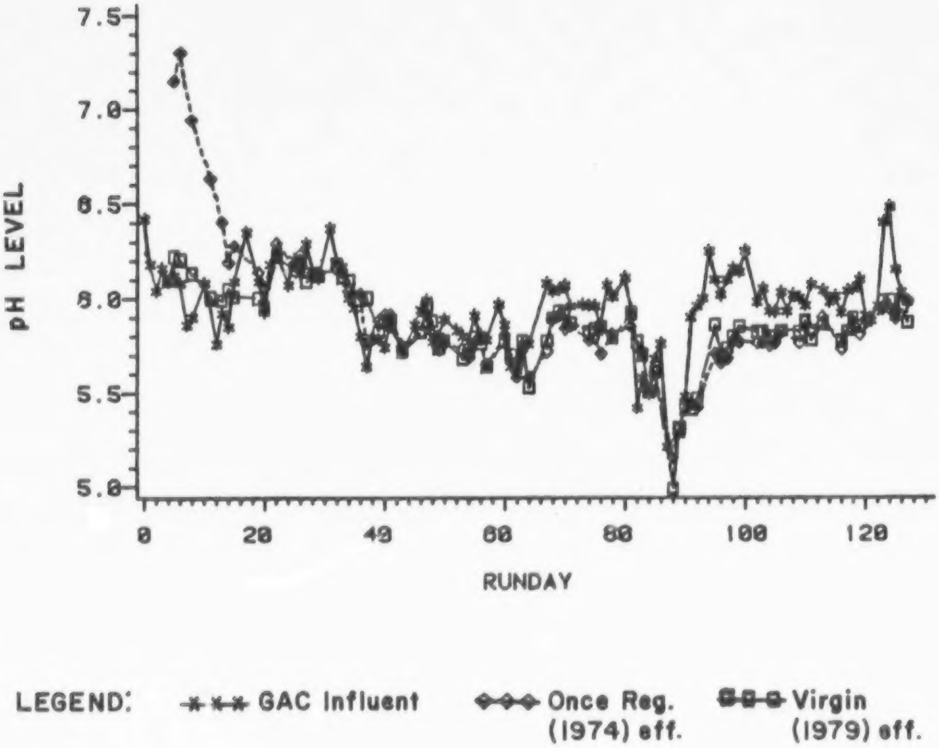


Figure 102. Run I.—Test filter pH vs. time.

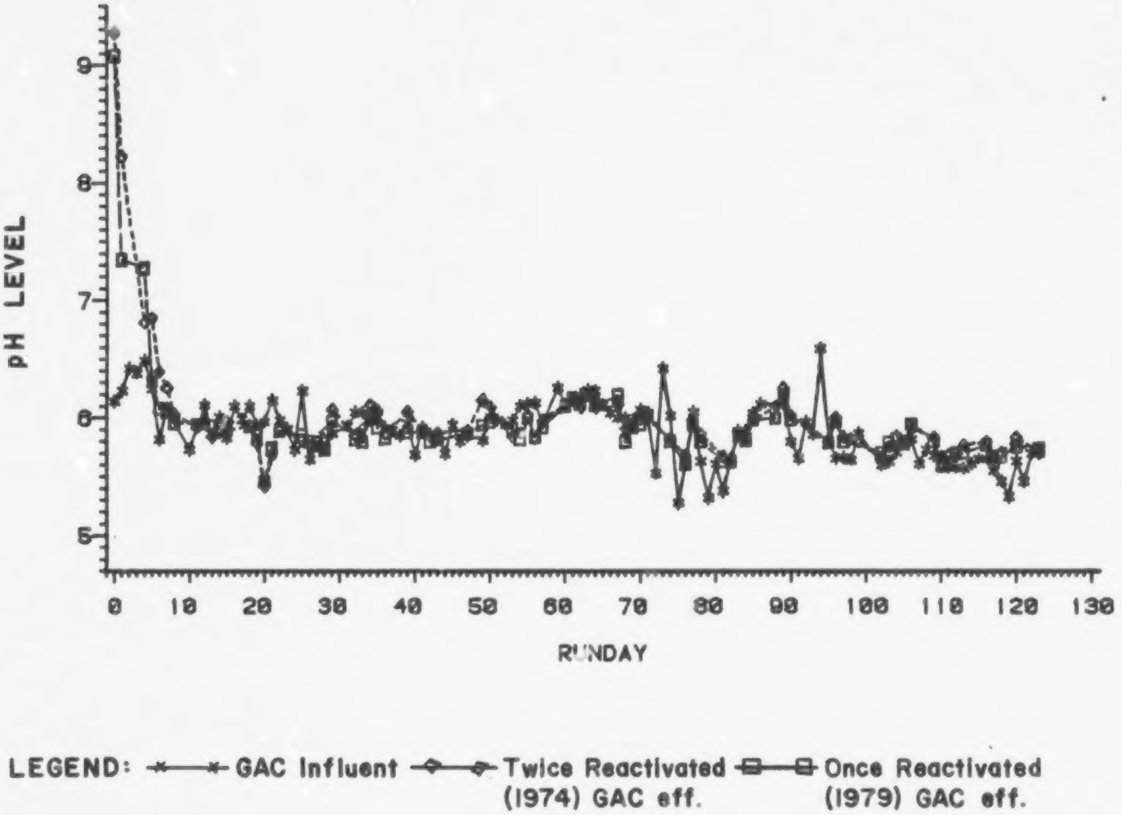


Figure 103. Run 2.—Test filter pH vs. time.

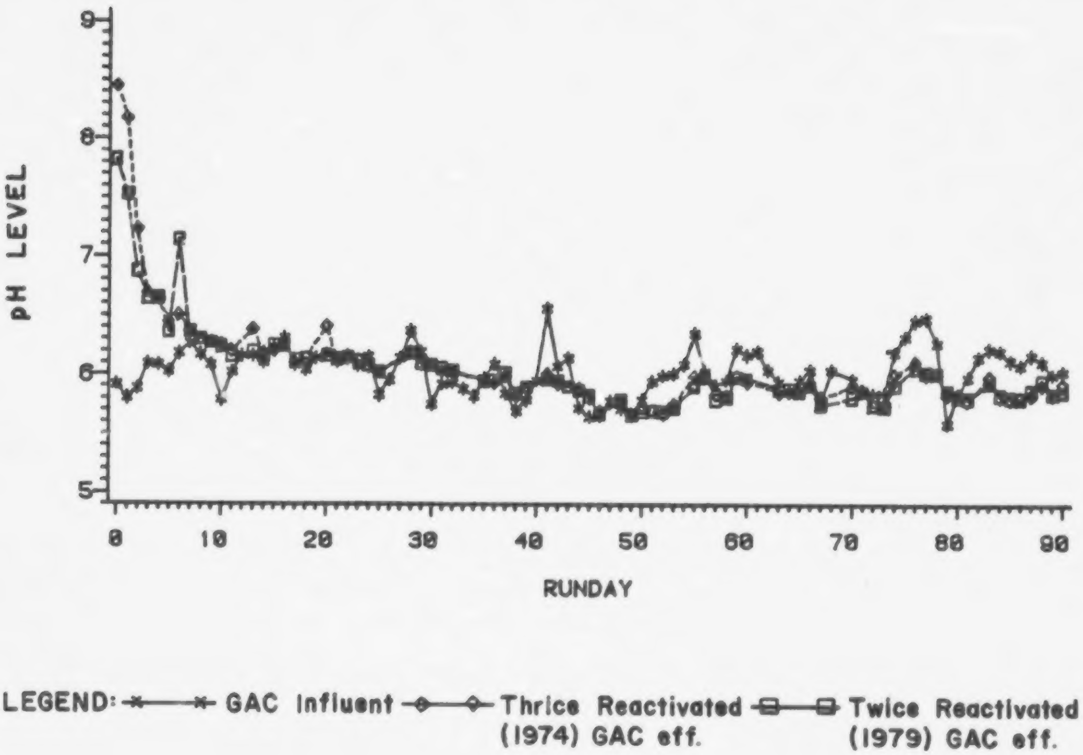


Figure 104. Run 3.—Test filter pH vs. time.

Dr. Stanton B. Smith, Doraville, GA. The analyses by MWW (see Appendix E) consisted of iodine number (IN, see procedure), decolorizing index (DI, see procedure), abrasion number (AN, see procedure) and calculations based on the SA to determine mean particle diameter (MPD). Independent lab analyses consisted of the analyses mentioned above plus modified phenol value (MPV), percent ash (%A), percent volatile (%V), BET surface area (BET), and nitrogen desorption pore size distribution (PSD).

The GAC characterizations by MWW were primarily performed on the fluid-bed reactivation system as a means for providing a measure of quality control during operation. When the reactivation system was operating at steady state, operations personnel collected daily grab samples of spent and reactivated GAC. Composite representative GAC samples were then analyzed weekly by MWW lab personnel utilizing a soil riffle sampler. Due to the relative ease and rapidity of measurement, the AD analysis was utilized most frequently to evaluate reactivator performance. Tables 19 and 20 detail the results of both MWW and outside GAC analyses for both spent and reactivated GAC properties.

The independent lab analysis work by Georgia Tech. and Dr. Smith was an attempt to characterize the test filter GAC before and after each monitoring run. The sample sites selected for these analyses were the test filter bed and the reactivator. In an attempt to correlate the GAC filter-bed sample sites to the sites of water intake for the water quality sampling system, 3 filter bed cells located approximately 3.3 M (10.7 ft), 6.6 M (21.4 ft) and 9.9 M (32.2 ft) from the opposite ends of the test filter-bed were sampled during this program. The 3 filter-bed samples from each end were then dried, composited and riffled to a representative volume. The sampling procedure used in gathering representative, full-depth GAC samples from the test filter consisted initially of manually digging out the filter-bed cells specified. During the process of digging out each cell, the sampler would collect a grab sample at .3, .6 and .9 M depths (1, 2 and 3 ft). These were then composited as a representative sample from that cell. To faciliate this sampling procedure, a device known as a "grain thief" was purchased (Figure 105). This device consists of 2 concentric brass tubes with the interior tube divided into 10 compartments and an exterior tube which when rotated, allows a given volume of sample to enter these compartments. The entire device is 5 cm diameter by 1.6 M long and is commonly used to sample grain from large storage bins. By inserting the device with compartments closed into the 1.2 M (4 ft) deep GAC filter-bed at the proper location, then opening the compartments, agitating the sampling device, then reclosing and withdrawing the device, a full-depth GAC sample was collected.

GAC samples were also collected at the reactivator during test filter reactivation. In an attempt to correlate the reactivator system samples with those taken directly from the test

TABLE 20

PHYSICAL CHARACTERISTICS OF ACTIVATED GAC

Property	Virgin 1974 GAC	Virgin 1979 GAC	1st Reactivation 1974 GAC	1st Reactivation 1979 GAC	2nd Reactivation 1974 GAC	2nd Reactivation 1979 GAC	3rd Reactivation 1974 GAC
Abrasion Number^1, % Mean		77.7	74.6	84.31	85.29	90.1	87.6
Abrasion Number^2, % Mean						90.1	87.6
Apparent Density^1		.614	.577	.596	.591	.574	.558
g/ml (lb/ft^3)		(38.3)	(36.0)	(37.2)	(36.9)	(35.8)	(34.8)
Apparent Density^2		.610	.576	.588	.586	.574	.558
g/ml (lb/ft^3)		(38.1)	(35.9)	(36.7)	(36.6)	(35.8)	(34.8)
Ash^1 Percent		5.42	7.33	6.13	7.21	6.31	7.25
BET^1 M^2/g		789	796	816.27	754.28	874.2	750.5
Iodine Number^1, mg/g	911	795	827	970	896	1203	1073
Iodine Number^2, mg/g		741	780			1203	1073
Mean Particle Diameter^1, mm		1.42	1.42	1.32	1.32	1.44	1.24
Mean Particle Diameter^2, mm		1.47	1.44			1.41	1.29
Mod Phenol Value^1 Westvaco mg/L		21.8	24.8	20.7	23.8	17.9	19.5
Molasses Decolorizing Index^1 DI/g		3.2	3.4	5.2	4.8	4.5	5.3
Molasses Decolorizing Index^2 DI/g		5.6	6.3			4.5	5.3
Volatile Matter^1, Percent		6.72	5.77	7.33	6.20	6.7	6.1

1. Data shown compiled from analyses performed by or under the auspices of Dr. Stan Smith, Doraville, GA with the exception of Virgin 1974 GAC.
2. Data shown compiled for analyses performed by the MWW, Manchester, NH.
3. Data shown compiled from analysis performed by B. C. Jensen, Westvaco, Chemical Technical Service Laboratory, Covington, VA.
4. All samples represent composited GAC samples taken from the test filter after backwashing, before put in service.
5. GAC evaluated is WESTVACO 8 x 30 WVW.

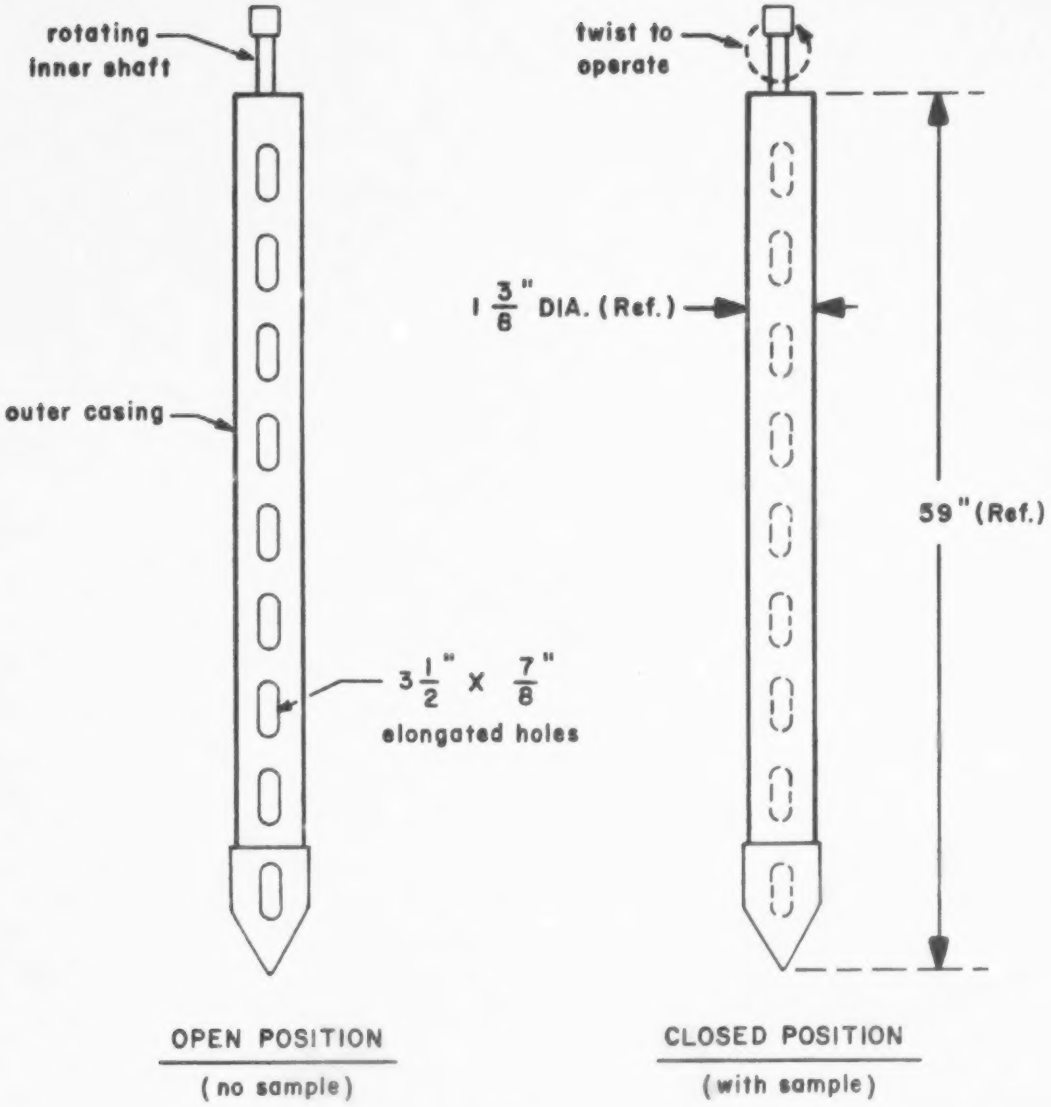

rotating inner shaft
outer casing
$3\frac{1}{2}$" X $\frac{7}{8}$" elongated holes
OPEN POSITION
(no sample)
twist to operate
$1\frac{3}{8}$" DIA. (Ref.)
59" (Ref.)
CLOSED POSITION
(with sample)

Figure 105. GRAIN THIEF

filter, collection of reactivator grab samples was made at approximately 24, 48 and 72 hours into the reactivation of each test filter half. By timing the reactivator sampling as such, these samples were expected to contain GAC originating at the filter-bed cells of 3.3, 6.6. and 9.9 M (10.7, 21.4 and 32.1 ft) from the test filter end walls. The location of the reactivator sampling sites was the dewatering screw outlet and the quench tank inlet. These are the points of spent GAC feed and reactivated GAC output of the fluid-bed system.

Laboratory GAC Characterizations Discussion

Graphic summaries of the averaged GAC lab results are presented in Figures 106 to 110. Except for BET and MPV, bar graphs of all the plots represent arithmetic mean values of the assembled data. Utilitizing these parameters as a guide, increases in IN, DI and MPV are seen for each reactivation. The BET surface area increased through 2 reactivations but then declined on the third reactivation. The measurements for AD and %V steadily declined with each reactivation, while the %A on the GAC steadily rose. Figures 110 and 111 indicate the changes in pore size distribution with each reactivation cycle. The 2 GAC "batches" were kept separate for clarity. Superimposing one graph on the other demonstrates that the PSD of the 2 batches is nearly identical. The particle size, abrasion resistance and apparent density analyses were found to be significant in this evaluation (Figures 112 to 115). The values for AD and MPD were observed to decline with each reactivation cycle.

The fluidizing gases of the reactivation system create sufficient upflow velocity to enable the system to act as a defining agent for all carbon particles falling below a critical weight/volume ratio. This suggests that there is a value at which the AD/MPD ratio becomes a sizeable factor in predicting losses to occur during reactivation. Another concern with reduction in AD and MPD values is the effect on filtration rates. Increased filter head loss and/or media removed through backwashing will result from reduced particle size diameter and density.

Summary of Test Filter Operation

Results of the water quality monitoring program and related testing work demonstrated that GAC adsorptive capacity was generally increased with each successive reaction. Runs #1 and #3 were conducted during increasing ambient water temperature conditions. Run #2 was performed during a period of declining water temperature. While temperature as well as organic loading varied from run to run, TOC and THMFP removals reached a steady state parameter reduction at no less than 40 days in all cases. Steady state removals were on the order of 30% of the influent concentration for TOC but varied widely for THMFP data.

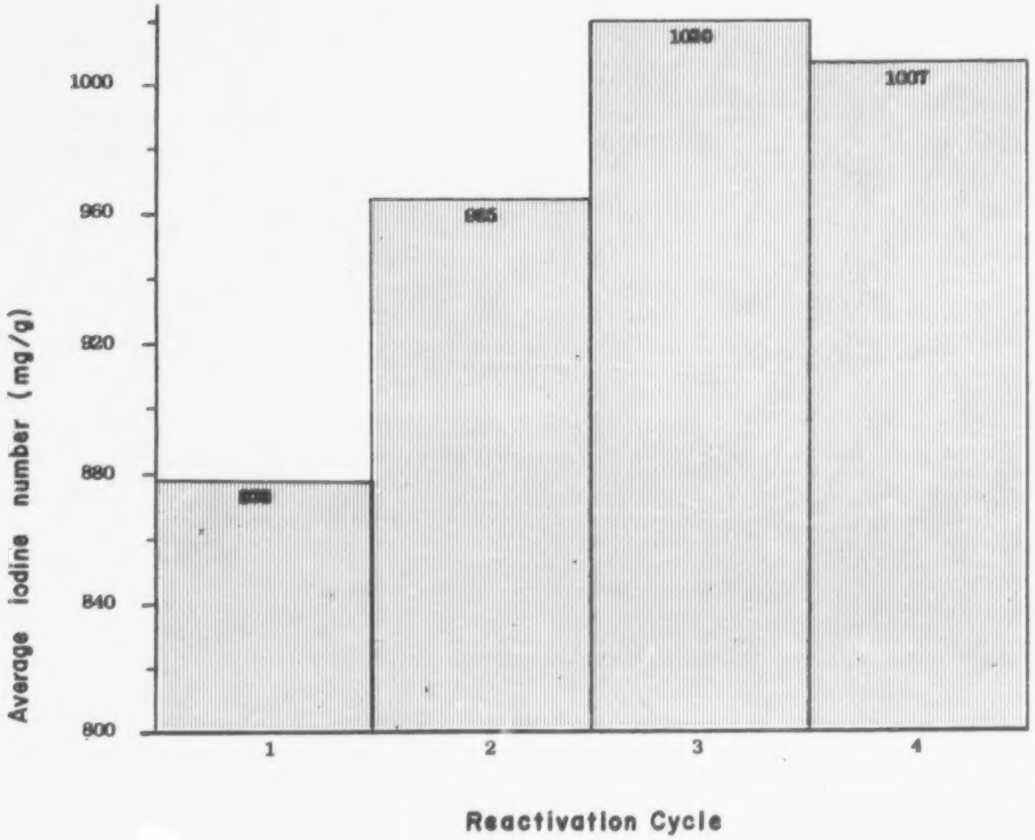


Figure 106. Iodine number vs. reactivation cycle.

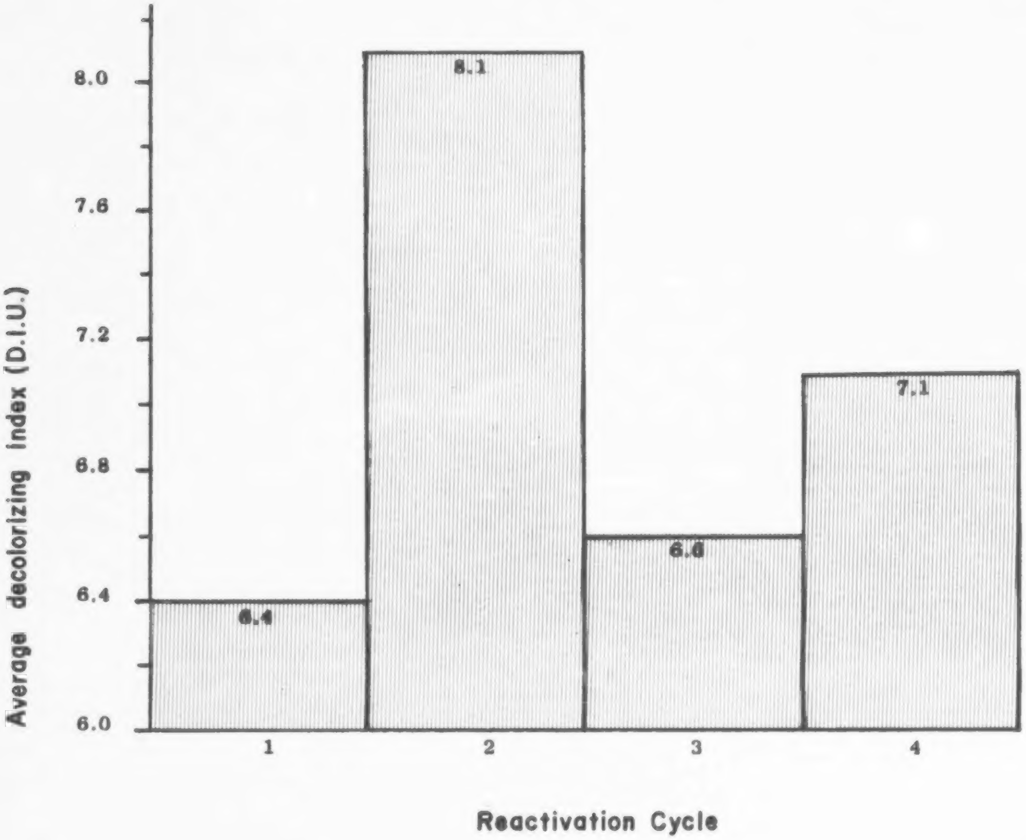


Figure 107. Decolorizing index vs. reactivation cycle.

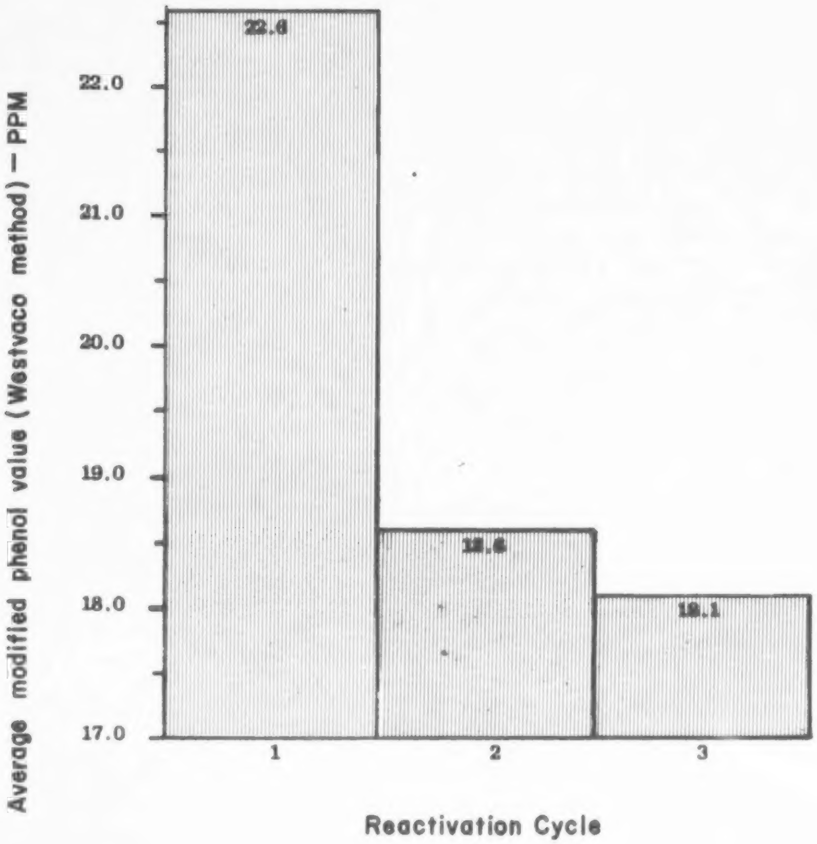


Figure 108. Modified phenol value vs. reactivation cycle.

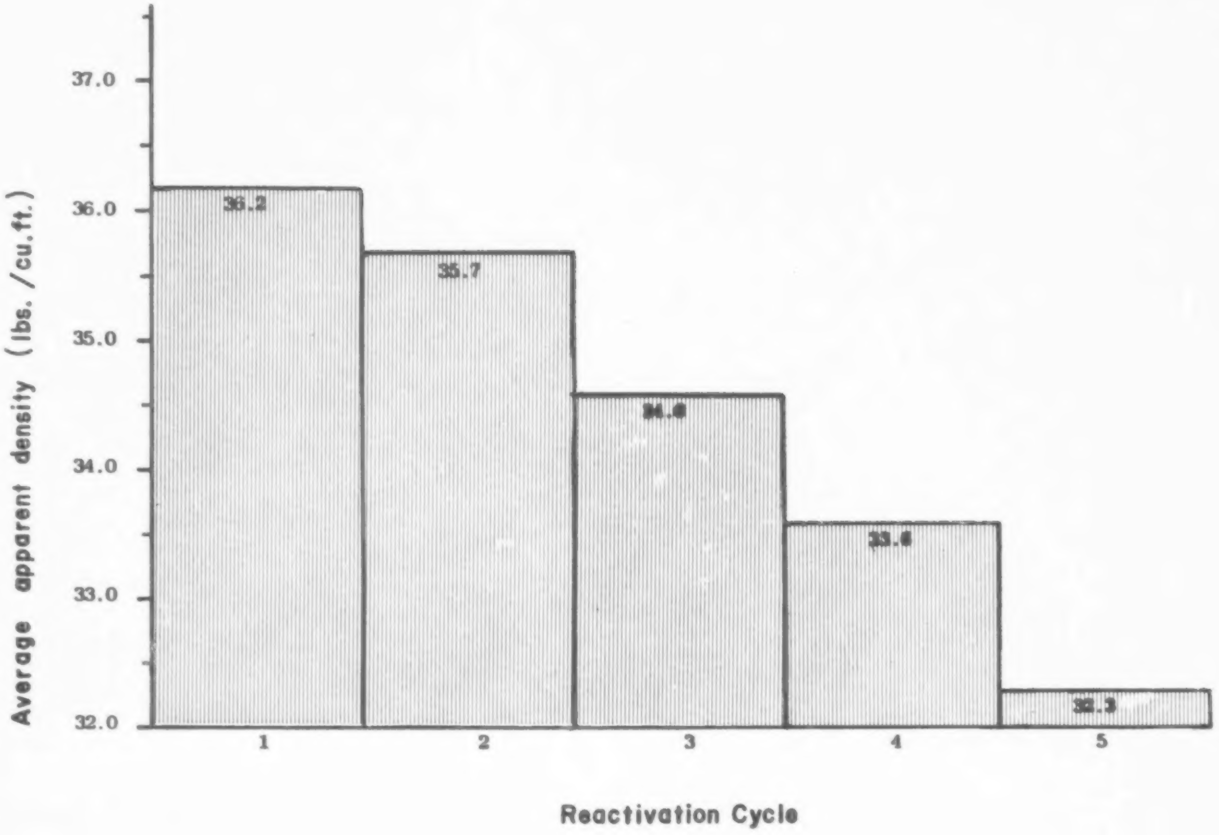


Figure 109. Apparent density vs. reactivation cycle.

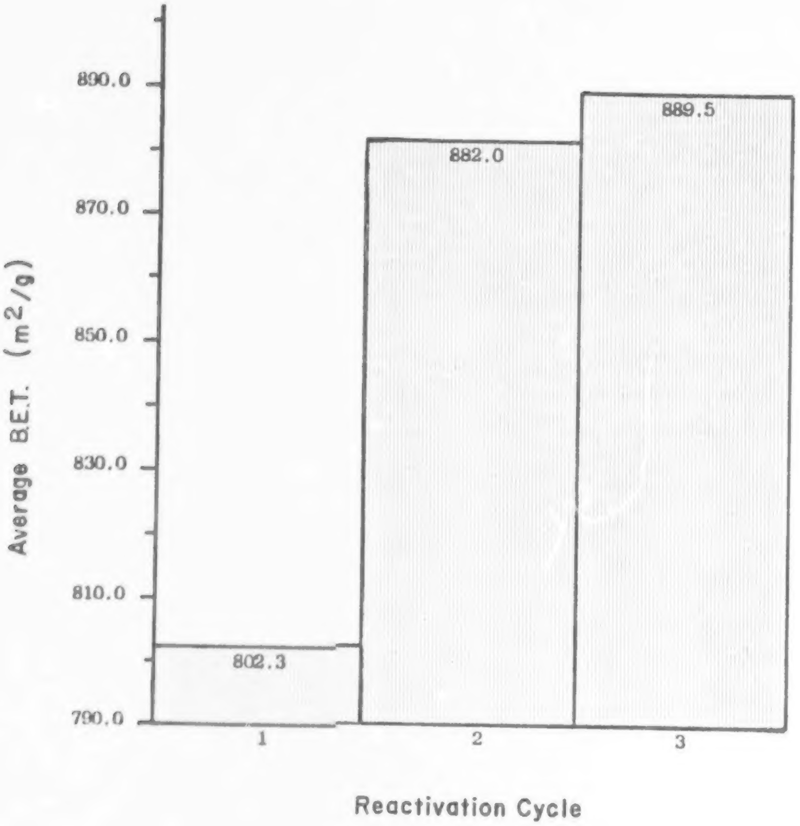


Figure 110. B.E.T. vs. reactivation cycle.

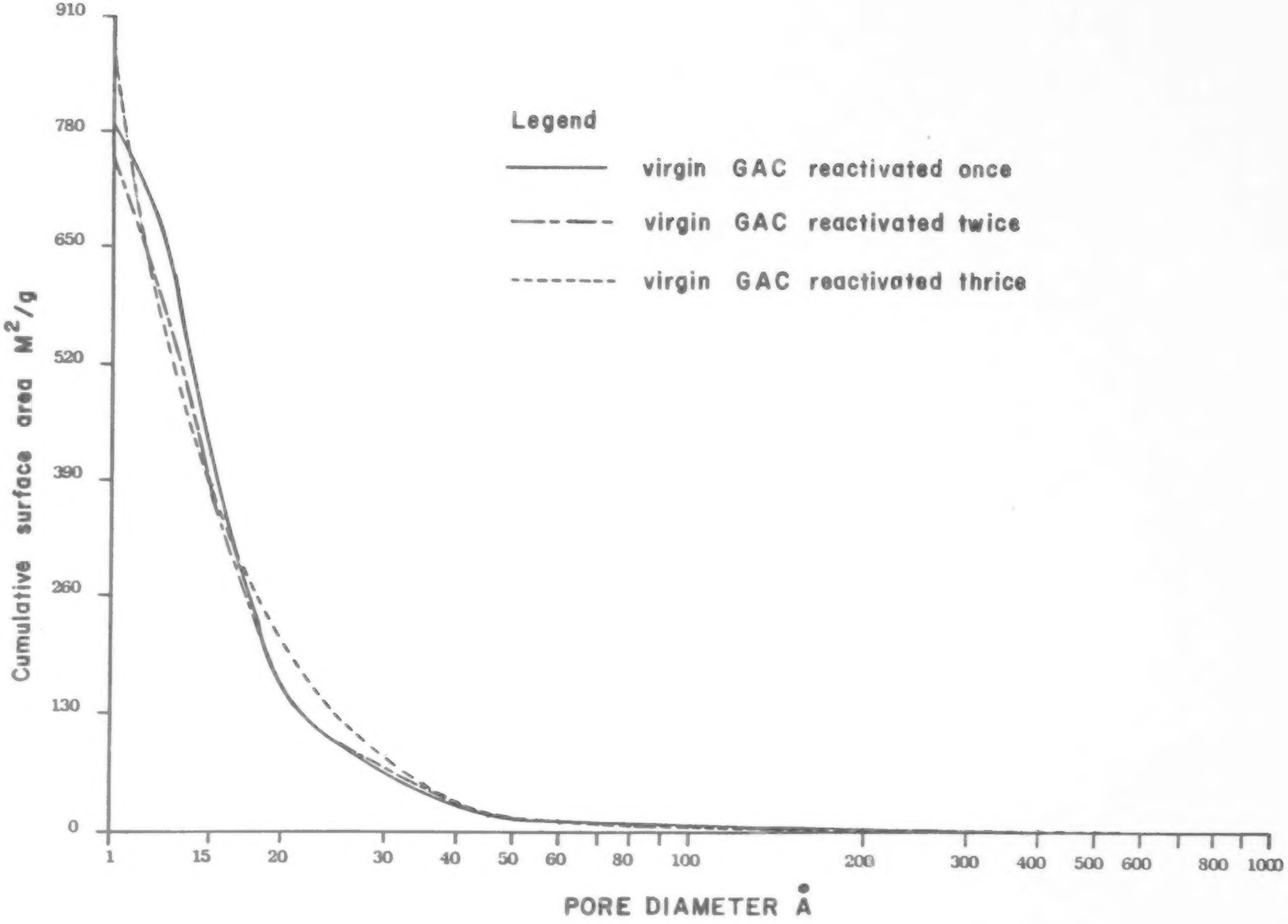


Figure III. Cumulative surface area distributions — Westvaco WVW, purchased 1979.

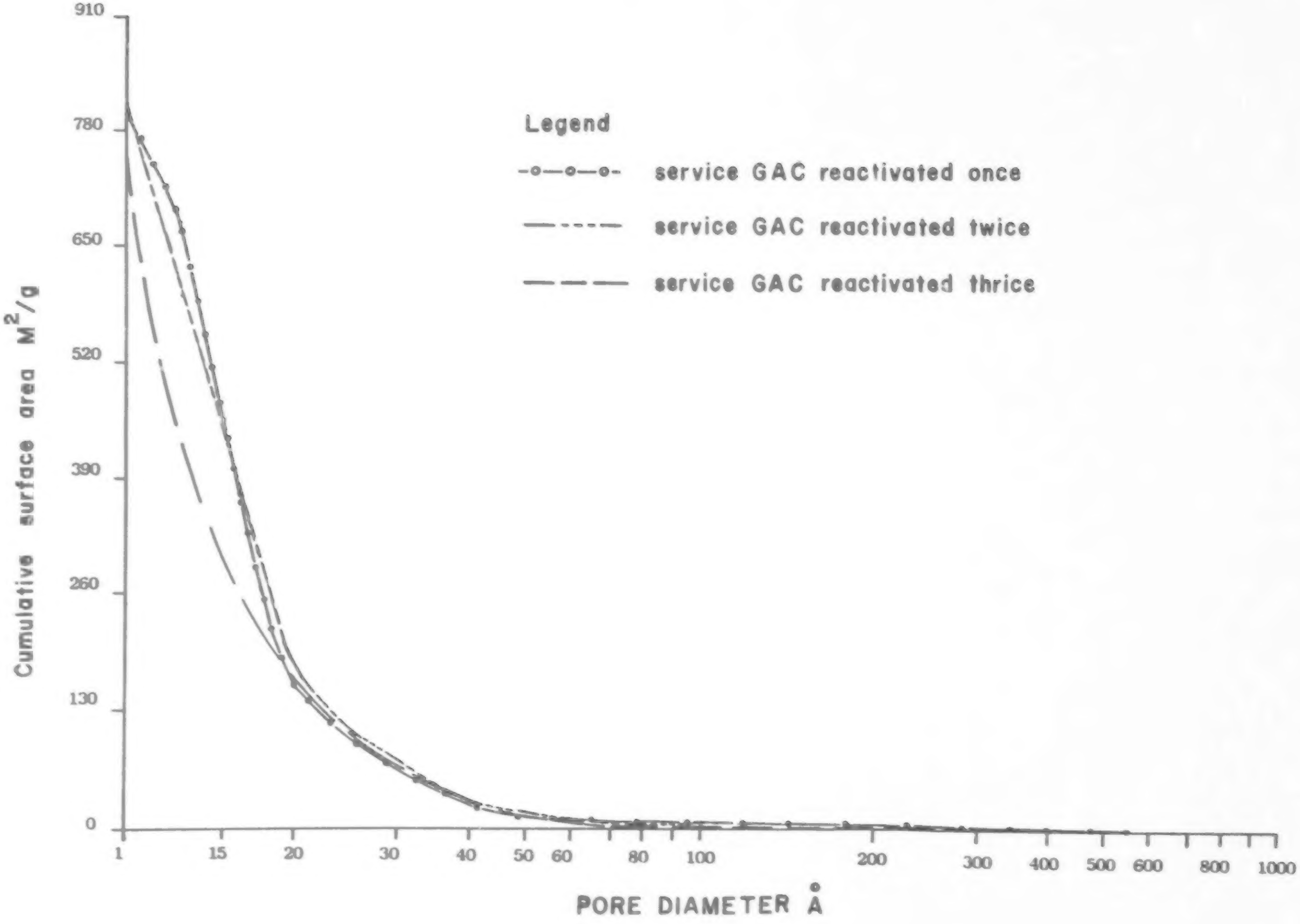


Figure 112. Cumulative surface area distributions — Westvaco WVW, purchased 1974.

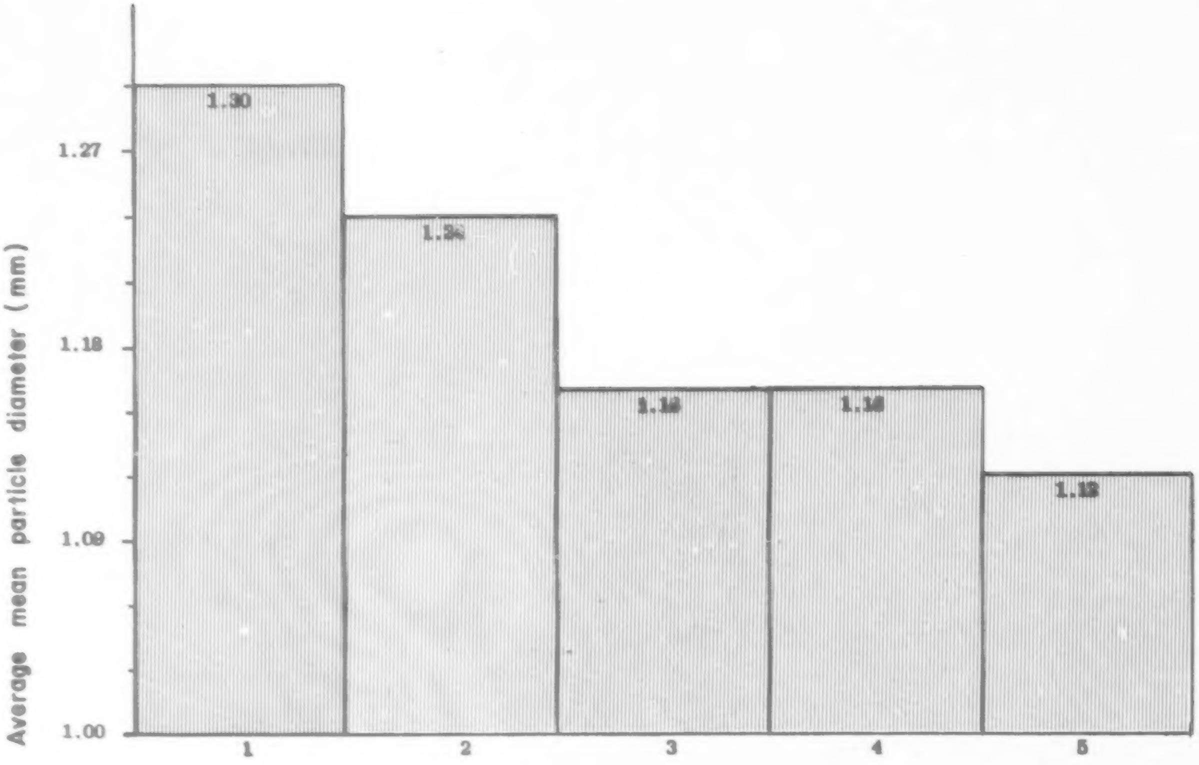


Figure II3. Mean particle diameter vs. reactivation cycle.

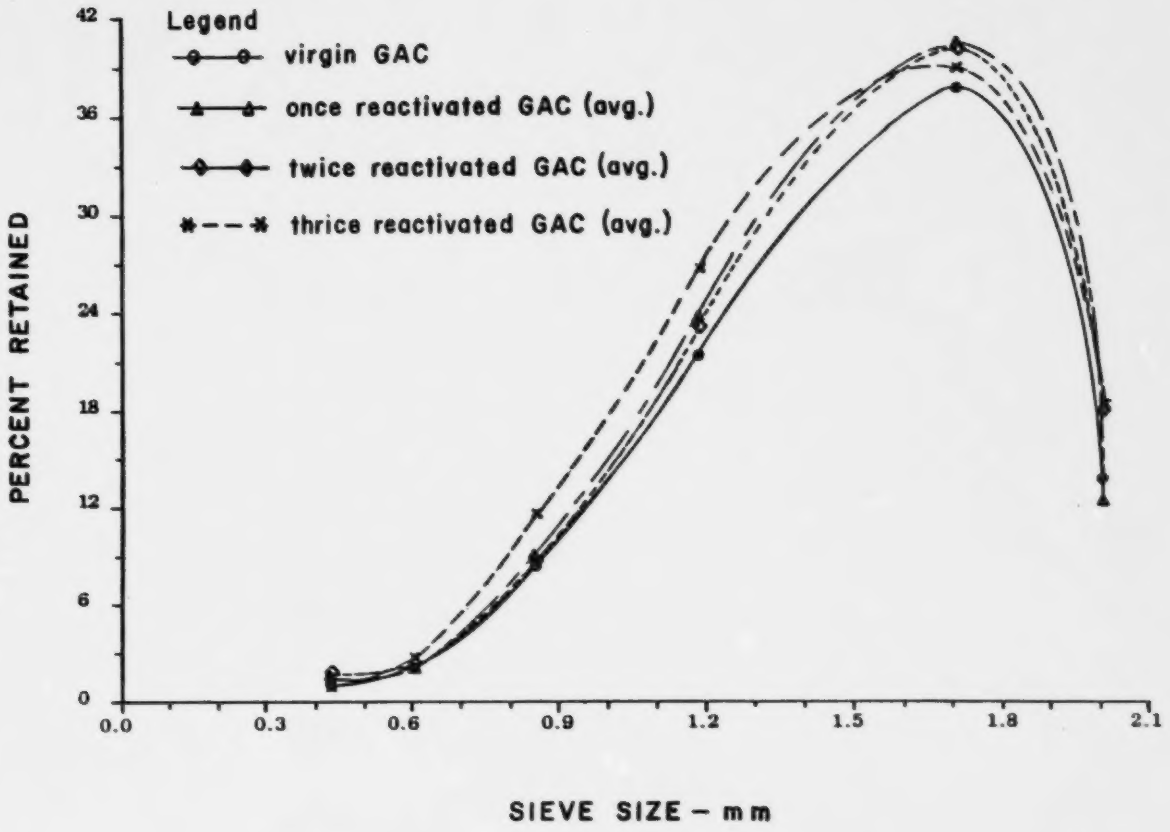


Figure 114. GAC particle size distributions.

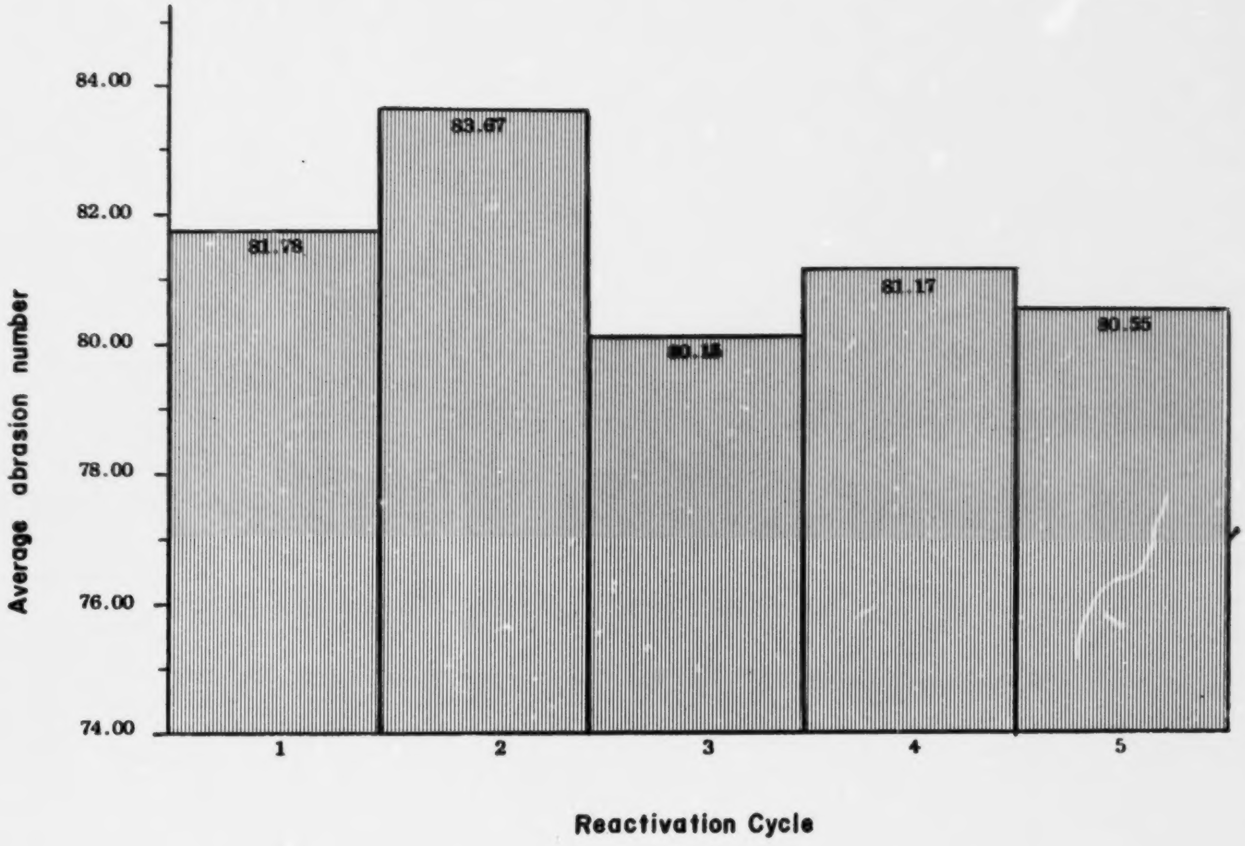


Figure 115. Abrasion number vs. reactivation cycle.

At equilibrium, little change in the average ITHM influent versus average ITHM effluent concentrations was detected. Depending on loading and temperature, ITHM equilibrium occurred anywhere from 25 to 70 run days.

A statistical analysis of the water quality data produced for TOC, ITHM, $CHCL_3$, and 3 and 7-day THMFP analyses is contained in Appendix C and is summarized in Table 21. A Gauss-Newton nonlinear least squares regression analysis was applied on a run by run basis in an attempt to determine the significance of the adsorptive recovery following reactivation. GAC loading curves were utilized for this analysis. The results indicate that the once reactivated GAC performed statistically better for TOC, ITHM and THMFP removal than virgin GAC. The statistical analysis verified the observation that upon subsequent reactivations, the loading capacity of the GAC becomes increasingly more uniform.

The GAC characterizations were indicative of changes occurring in the relative adsorptive capacity of the GAC following reactivation. However, they were not specific enough to be used alone as indicators of the predicted true behavior of GAC for adsorption of organic contaminants. The particle size and apparent density reductions observed during each reactivation are important considerations in determining GAC filter performance. Therefore, these values must be closely monitored with lower limits established for each, based on head loss and backwashing considerations.

Additional data gathered but not presented here is contained in graphical form in Appendix B.

TABLE 21

SUMMARY OF t STATISTICS FOR INTERRUN EVALUATION OF TOC, ITHM, $CHCL_3$ AND THMFP (3 AND 7-DAY AMBIENT) BREAKTHROUGHS[1]

Parameters		Run #1	Run #2	Run #3
TOC	K	1.99	2.00	1.85
	C	46.9	10.0	2.80
	R	0.447	0.52	2.70
ITHM	K	3.89	1.78	0.68
	C	83.9	3.75	3.14
	R	11.5	0.89	0.769
$CHCL_3$	K	1.07	2.03	0.22
	C	70.4	4.02	1.91
	R	3.74	1.19	0.408
THMFP 3 Days @ Amb. Temp.	K	3.2	1.10	2.10
	C	45.6	9.18	1.38
	R	3.97	0.32	0.642
THMFP 7 Days @ Amb. Temp.	K	1.26	0.75	0.108
	C	19.6	3.58	4.28
	R	0.56	0.655	0.208

NOTE: $t_{.995} = 2.66$
$t_{.975} = 2.00$

K, C, and R are the coefficients in the equation $y = C/(1 + Ke^{-RT})$ solved for iteratively by curve fitting to the actual data curves.

Run #1: Virgin Vs. Once Reactived
Run #2: Once Reactivated Vs. Twice Reactivated
Run #3: Twice Reactivated Vs. Thrice Reactivated

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[1] John Ireland, "Statisticaly Analysis of Breakthrough Curves", Appendix C.

SECTION 10

PHASE III: GAC REGIONAL REACTIVATION PROGRAM

Purpose and Scope - Phase III

1. To determine the cost and performance of a regional GAC reactivation system.
2. To establish the economic feasibility of providing a future GAC reactivation service for other water utilities in the New England region.

Regional Reactivation Operational Research - Phase III

Having achieved all the initial objectives of the Phase II Program, some effort was needed to investigate the future use of the carbon reactivation facility. For this reason, the possibility of using the Manchester facility as a regional reactivation center was explored. For effective taste and odor removal, past experience has demonstrated that Manchester's carbon will require reactivation at a frequency of about once every two to four years, depending on seasonal variations in raw water quality. The optimum throughput capacity of the Manchester reactivator is approximately 5,987 kg (13,200 lbs) of GAC per day, or about 1.63 million kg (3.6 million lbs) per year (assuming a reasonable operating factor of about 75%). Thus, it would take less than 4 months to reactivate the entire 0.45 million kg (one million lbs) of GAC in the Manchester Treatment Plant.

Since the reactivator has a capacity which is substantially greater than the reactivation requirements of the Manchester Water Works, it was reasonable to conclude that some portion of this proposal to utilize the excess capacity could be used to reactivate GAC for other water utilities in the region. Therefore, the feasibility of developing a regional reactivation program was evaluated.

The initial step in this regional research effort was to conduct a survey of water utilities in New England who use GAC and their estimated yearly reactivation requirements. Consulting engineering firms in the area assisted the Manchester Water Works in identifying these utilities. There are presently (December

1981) 19 water treatment plants in New England using GAC, and each utility was contacted in order to assemble a data base for overall evaluation, and the results of this survey are shown in Table 22.

The combined total of all the GAC in New England water treatment plants is about 1.68 million kg (3.7 million lbs). The smallest facility has about 5,897 kg (13,000 lbs) while the largest plants, Manchester, NH and Lowell, MA have about 0.45 million kg (one million lbs) of carbon each. Eleven treatment plants are located in Massachusetts, 3 in New Hampshire, 1 in Maine, and 1 in Rhode Island. No GAC treatment facilities were identified in the state of Vermont. GAC from a number of the major suppliers (Westvaco, Calgon, ICI and Carbonundum) was identified in this survey.

The major purpose for utilizing GAC in all but one of the water treatment facilities was to control taste and odor compounds. Laconia, NH, the sole exception, uses GAC for dechlorination. The various taste and odor loadings create a reactivation frequency ranging from once each year to once every 5 years. Shown in Table 22 are the 19 water treatment plants and their estimated reactivation requirements over the next 4 years. Yearly reactivation requirements range from a high of about 0.77 million kg (1.7 million lbs) in 1984 to a low of about 362,874 kg (800,000 lbs) in 1982. These figures also include Manchester's reactivation needs. Even if Manchester were to reactivate its own GAC and that of all the other utilities at the estimated reactivation frequency for each plant, the maximum reactivator capacity of 1.63 million kg (3.6 million lbs) per year would be less than half utilized.

A very important aspect of any regional reactivation program would involve the transportation of the carbon media to and from the reactivator. In the regional concept, the transportation and reactivation of carbon are integrally related. The first step in evaluating the transportation aspect was to locate all the various utilities with reference to Manchester (Table 23). Twelve of the utilities are within a 97 kilometer (60 mile) radius of Manchester. The other 7 treatment plants are located a greater distance away with the 3 Connecticut plants being located approximately 241 kilometers (150 miles) from Manchester.

Significantly, all of the utilities contacted indicated that they were interested in carbon reactivation service being provided to them by Manchester. After careful evaluation of the considerations, a limited regional reactivation program was pursued. Initial contact was made with 3 water utilities to reactivate approximately 18,144 kg (40,000 lbs) of GAC from each off-site treatment plant; namely, (1) Kelseytown, Connecticut Water Treatment Plant, (2) Danvers, Massachusetts Water Treatment Plant, and (3) Lowell, Massachusetts Water

TABLE 22

GAC REGIONAL REACTIVATION PROGRAM
NEW ENGLAND WATER UTILITY ESTIMATED YEARLY REACTIVATION REQUIREMENTS

UTILITY	1982		1983		1984		1985	
	KGS	LBS	KGS	LBS	KGS	LBS	KGS	LBS
Chester, CT.			13,154	29,000			13,154	29,000
Kelseytown, CT			43,545	96,000				
Middleton, CT							55,338	122,000
Kittery, ME					19,504	43,000		
Amesbury, MA					34,019	75,000		
Billerica, MA	22,680	50,000	22,680	50,000	22,680	50,000	22,680	50,000
Burlington, MA								
Danvers, MA	40,823	90,000	40,823	90,000	40,823	90,000	40,823	90,000
Essex, MA								
Hanverhill, MA								
Lawrence, MA	99,790	220,000	99,790	220,000	99,790	220,000	99,790	220,000
Lowell, MA	113,398	250,000	113,398	250,000	113,398	250,000	113,398	250,000
Methuen, MA					56,699	125,000	56,699	125,000
Scituate, MA					8,618	19,000		
Somerset, MA							9,072	20,000
Claremont, NH					72,575	160,000		
Laconia, NH								
Manchester, NH			113,398	250,000	113,398	250,000	113,398	250,000
Pawtucket, RI	90,718	200,000	90,718	200,000	90,718	200,000	90,718	200,000
YEARLY TOTALS	367,410	810,000	537,507	1,185,000	790,611	1,743,000	615,071	1,356,000
PERCENT OF REACTIVATOR YEARLY FURNACE CAPACITY		22%		33%		48%		38%

TABLE 23

APPROXIMATE ONE WAY DISTANCE FROM MANCHESTER, NH TO NEW ENGLAND WATER TREATMENT PLANTS USING GAC

LOCATION	KILOMETERS	(MILES)
Claremont, NH	100	(62)
Laconia, NH	71	(44)
Kittery, ME	97	(60)
Amesbury, MA	68	(42)
Newburyport, MA	80	(50)
Haverhill, MA	51	(32)
Lawrence, MA	48	(30)
Methuen, MA	48	(30)
Lowell, MA	53	(33)
Essex, MA	84	(52)
Danvers, MA	66	(41)
Burlington, MA	76	(47)
Scituate, MA	127	(79)
Billerica, MA	68	(42)
Pawtucket, RI	150	(93)
Somerset, MA	164	(102)
Middleton, CT	233	(145)
Chester, CT	241	(150)
Kelseytown, CT	277	(172)

Treatment Plant. Prior to starting any reactivation for the two Massachusetts utilities, the approval of the State Department of Environmental Quality Engineering (DEQE) was necessary. DEQE endorsed this proposal by Manchester and field work began in the fall of 1981.

The first priority of this new program was to locate trucks that were capable of hauling GAC between each of the 3 utilities and Manchester. After investigating several alternatives, the most cost effective approach was to rent transportation equipment from local trucking firms. The type of vehicle selected was an open top trailer dump truck. The body of the trailer had a volumetric capacity of about 34.0 cubic meters (1,200 cubic feet) which corresponded with the volumetric capacity of the spent and reactivated storage tanks in the reactivator building (33.3 cubic meters or 1,176 cubic feet). The only modification that was made to the truck was to construct a watertight tailgate to ensure that there would be no road spillage. The tailgate of the truck was fabricated of 0.635 cm (quarter-inch) mild steel plate and installed by Manchester Water Treatment Plant personnel. Necessary transport licenses to haul the GAC were obtained from the (ICC) regional office in Boston, MA.

The amount of GAC that could be hauled over the road is governed by state laws which stipulate that the gross weight of the vehicle and load cannot exceed 36,287 kg (80,000 lbs. Because the empty vehicle weight of the tractor and trailer is about 15,876 kg (35,000 lbs), this meant a payload of about 20,412 kg (45,000 lbs) could be hauled. Also, since wet drained GAC weighed roughly twice as much as the dry carbon, two separate hauls were required to reactivate the 18,144 kg (40,000 lbs) of dry carbon for each utility. The sequence of transporting the carbon was as follows:

A. Dispatch an empty truck to the participating utility.
B. Return truck to Manchester with a load of drained-wet spent GAC approximately 18,144 kg (20 tons).
C. Reactivate approximately 18,144 kg (20 tons) of GAC (dry basis) at Manchester.
D. Return the reactivated GAC to the utility.
E. Pick up a second load of drained-wet GAC from the utility and return to Manchester.
F. Reactivate the second load of spent GAC.
G. Return to the utility the second reactivated load of GAC.
H. Proceed to the next utility and repeat the sequence.

The first utility which participated in the regional program was the Connecticut Water Company and its Kelseytown Water Treatment Plant. This was followed by reactivation work at Danvers, MA Water Treatment Plant, and the Lowell, MA Water Treatment Plant, respectively. The details of each reactivation at each utility is shown in Tables 28, 32 and 36. The

Connecticut plant, located the furthest distance from Manchester is 277 kilometers (172 miles), or a travel time of about 3-1/2 hours. The Danvers and Lowell plants are located 66 and 53 kilometers (41 and 33 miles), respectively, from Manchester. All 3 are conventional water treatment plant using GAC primarily for taste and odor removal. The plants average daily flow ranges from 9,463 to 45,425 m^3 (2,500,000 to 12,000 gallons) per day.

Loading and off-loading GAC from the trailer truck was accomplished using a 7.62 cm (3 in) eductor and polyvinyl hose. The time required to fill the truck was in the range of 4 to 5 hours while off-loading the truck took about 1-1/2 to 2-1/2 hours. This difference in filling time versus emptying time was because a constant flow of GAC was provided to the eductor during the empty cycle as opposed to an intermittent type flow during the fill cycle. Once the GAC arrived at Manchester, reactivation of the 9,072 kg (20,000 lbs) truckload was accomplished in approximately 40 hours. The reactivation process was very routine and similar to what Manchester had been experiencing during the previous 2 years with its own GAC. Carbon feed rates, temperatures and pressures varied slightly due to the different grades of GAC and adsorbate loadings but process adjustments were easily made to ensure a high activity reactivation.

Overall, the program went extremely well; the reactivator performed with few problems, and the transportation of the GAC went smoothly. All 3 utilities were very cooperative which helped ensure the success of the program. Only minor problems were encountered and those were at the Lowell, MA facility which lacked a paved driveway along the filter building to accommodate the trailer truck. Also, strong chlorine gas vapors were released from the GAC as a result of raw water super chlorination and there was some difficulty in dewatering the filter bed due to plant hydraulics. All 3 of these problems were readily resolved, although future reactivation work at Lowell will require the utility to improve the driveway area, adjacent to the filter room.

The only significant recommendation that could be incorporated into future regional reactivation programs would be the use of 2 trailer trucks to transport the GAC, rather than 1 as used in the experimental program. When utilizing just 1 truck, it was necessary to shut down the reactivator and stop processing GAC while waiting for the truck to return with another load of carbon. A 2-truck operation would ensure that there was always a continuous flow of GAC to the reactivator, thereby, eliminating the need to shut down reactivator operations. Inefficiency also resulted because fuel, power, water, etc. were being consumed by the equipment for several hours in order to bring the furnace up to reactivation temperature in the startup phase and, then, the burnoff of carbon in the reactivator during the shutdown phase. The addition of a second truck was found to be the only major improvement required to establish an effective regional reactivation facility at Manchester, NH.

Analytical - Phase III

The Phase III Analytical Program was designed to provide basic information necessary to determine the effectiveness of the reactivation process on each GAC sample site studied (Table 24). All analyses were performed inhouse at the MWW lab. The GAC samples analyzed were composites of 6 grab samples gathered before and after reactivation. Aqueous sampling for TOC, ITHM and THMFP was done by the participating utilities forwarding the samples to the MWW for analyses (Table 24). TOC, ITHM and THMFP analyses were performed comparing the utilities service GAC with freshly reactivated GAC. These analyses were repeated at 1 and 2 months of filter service. While not intended as any sort of conclusive side by side evaluation, it was hoped to provide a data base for further analyses. Any supplemental analyses providing a more indepth evaluation would be performed either by the participating utility or by their consultants.

In order to fully evaluate the performance of the reactivated GAC at each utility, a control would be required. This control should consist of monitoring virgin and reactivated GAC effluents as was done in Manchester. Comparison of the virgin data with the reactivated GAC effluent data would establish the effectiveness of the reactivation on the GAC.

Although we performed only a cursory GAC property evaluation, it did indicate that the GAC was reactivated to a virgin state. This was shown in the GAC characterization data where the iodine numbers were returned to virgin levels without exception (Tables 25, 26 and 27). However, the mean particle diameter (MPD) analyses did demonstrate an abnormally high decrease in average particle size. The range of the decrease in mean particle size was 19 to 24%, and not characteristic of the 5 to 10% reduction Manchester had experienced in reactivating its own carbon. Perhaps, the additional transport phase or the difference in GAC specification is responsible for this difference.

Cost Analysis - Phase III

The cost of reactivating approximately 18,144 kg (40,000 lbs) of GAC for each of the regional utilities taking part in this research program (CT Water Co., Lowell MA and Davers, MA) is shown in Tables 28 to 40. GAC reactivation work was performed in November and December 1981, and the total cost based on actual charges for labor, materials and related costs existing at that time. The cost of reactivating GAC from Lowell and Davers, MA was somewhat comparable, i.e., 99.09¢/kg (44.95¢/lb) and 82.68¢/kg

TABLE 24

REGIONAL MONITORING SCHEDULE

PARAMETER	SAMPLING POINT	FREQUENCY
Iodine Number	Fluid-Bed Reactivator	One composite sample was made from 3 grab samples taken on an evenly timed basis from reactivator feed and reactivator product sampling sites.
Apparent Density	Fluid-Bed Reactivator	
Sieve Analysis	Fluid-Bed Reactivator	
Abrasion Number	Fluid-Bed Reactivator	
Volumetric Losses[5]	Fluid-Bed Losses	One analysis per batch (truckload)
Total Organic Carbon	GAC Influent and Effluents	To[1]; T_1Month[2]; T_2Month[3]
Instantaneous Trihalomethanes	GAC Influent and Effluents	To[1]; T_1Month[2]; T_2Month[3]
7 Day 28.5°C Trihalomethane Formation Potential[4]	GAC Influent and Effluents	To[1]; T_1Month[2]; T_2Month[3]

Note:

1. To - Start of GAC operation after reactivation.
2. T_1 - Approximately one month of continuous service after reactivation.
3. T_2 - Approximately two months of continuous service after reactivation.
4. TTHM (7M) - Terminal trihalomethane formation potential based on 7 days at pH 8 and 28°C.
5. Reference Appendix C: Fluid-Bed Volumetric Loss Analysis

TABLE 25

MWW REGIONAL REACTIVATION PROGRAM

UTILITY Connecticut Water Co. TYPE AND GRADE OF GAC Carborundum 8 x 30

Physical Carbon Analyses

	Apparent Density (lbs/ft^3)	Iodine No. (mg/g)	Abrasion No. (%)	Mean Particle Diameter (mm)	Sieve Analysis (% Retained on Sieve)							
					> 6	6 x 8	8 x 12	12 x 16	16 x 20	20 x 30	30 x 40	PAN
Spent	28.2	≈ 380	53.80	1.58	0	.02	36.97	54.54	5.81	1.72	0.58	0.36
Reactivated	24.8	≈ 660	59.59	1.46	0	.03	25.21	53.14	11.44	4.66	0.96	0.16

Aqueous Data

Location	Time (Mos.)	TOC (mg/l)	ITHMS (μg/l)	THMFP 7 Days @ 28.5°C (μg/l)
GAC - Influent	0	1.7	< 1.0	166
	1	1.4	4.8	155
	2	1.1	2.4	80
Reactivated GAC - Effluent	0	0.6	< 1.0	69.2
	1	0.9	2.2	74.1
	2	1.1	1.2	77.3
Non-reactivated GAC - Effluent	0	1.1	< 1.0	106
	1	1.4	6.8	153
	2	2.1	3.9	50.1

TABLE 26

MWW REGIONAL REACTIVATION PROGRAM

UTILITY Danvers, Massachusetts TYPE AND GRADE OF GAC Calgon Filtrasorb 300 12 x 40

Physical Carbon Analyses

	Apparent Density (lbs/ft^3)	Iodine No. (mg/g)	Abrasion No. (%)	Mean Particle Diameter (mm)	Sieve Analysis (% Retained on Sieve) >6	6 x 8	8 x 12	12 x 16	16 x 20	20 x 30	30 x 40	PAN
Spent	37.0	664	86.93	1.53	0	6.73	33.44	30.19	18.33	8.93	1.86	0.52
Reactivated	33.7	985	82.76	1.16	0	1.29	15.60	25.70	25.68	25.68	8.89	1.36

Aqueous Data

Location	Time (Mos.)	TOC (mg/l)	ITHMS (µg/l)	THMFP 7 Days @ 28.5°C (µg/l)
GAC - Influent	0	6.2	22.9	569
	1	5.4	29.7	440
	2	4.3	19.4	263
Reactivated GAC - Effluent	0	0.7	≤0.5	121
	1	1.6	7.4	147
	2	2.6	12.1	201
Non-reactivated GAC - Effluent	0	4.0	18.1	342
	1	4.1	22.3	327
	2	3.5	10.7	261

TABLE 27

MWW REGIONAL REACTIVATION PROGRAM

UTILITY Lowell, Massachusetts TYPE AND GRADE OF GAC Westvaco 8 x 30

Physical Carbon Analyses

	Apparent Density (lbs/ft^3)	Iodine No. (mg/g)	Abrasion No. (%)	Mean Particle Diameter (mm)	Sieve Analysis (% Retained on Sieve)							
					>6	6 x 8	8 x 12	12 x 16	16 x 20	20 x 30	30 x 40	PAN
Spent	35.3	640	79.02	1.43	.08	4.93	25.41	34.07	22.36	9.53	2.02	1.60
Reactivated	31.7	1,025	71.55	1.16	.02	1.19	12.22	29.07	30.17	19.19	6.41	1.73

Aqueous Data

Location	Time (Mos.)	TOC (mg/l)	ITHMS (μg/l)	THMFP 7 Days @ 28.5°C (μg/l)
GAC - Influent	0	2.7	26.0	87.0
	1	-	-	-
	2	1.6	33.0	87.0
Reactivated GAC - Effluent	0	0.3	17.5	29.0
	1	-	-	-
	2	0.8	15.0	55.7
Non-reactivated GAC - Effluent	0	1.5	23.5	65.5
	1	-	-	-
	2	1.5	21.7	84.3

(37.50¢/lb), respectively. However, the cost of reactivating GAC for the Connecticut Water Co. at 146.04¢/kg (66.24¢/lb) was found to be considerably higher for two reasons: 1) higher carbon losses and 2) greater transport distance between the utilities. The total volumetric carbon loss was 23.5% at Connecticut, 15.3% at Lowell, and 11.4% at Danvers. A possible reason for the higher GAC losses could be due to the fact that the Connecticut carbon was a lignite base filter media whereas Danvers and Lowell use a carbon base media. Since it is recognized that lignite base carbon media is softer than coal base carbon, it is suspected that abrasion losses would be greater in the lignite material.

The total cost for transporting the Connecticut GAC (cost item C plus Cl, Table 29 was 16.51¢/kg (7.49¢/lb) compared to 12.06¢/kg (5.47¢/lb) and 9.67¢/kg (4.39¢/lb) for the Danvers and Lowell, MA carbon, respectively. The reason for this higher transport cost for the Connecticut utility is because the treatment plant is more than 4 times the travel distance between Manchester and the other 2 regional utilities.

A summary of the total reactivation cost for each of the utilities along with the cost for virgin makeup carbon is shown in Table 28. Attempts to draw comparisons between the cost of reactivation and the cost of virgin makeup carbon are not valid because the quantities of virgin makeup carbon involved were small which resulted in higher purchase costs. The commercial market pricing for virgin GAC is structured on a cost-to-quantity basis, i.e., the smaller the quantity the greater the cost.

TABLE 28

MWW REGIONAL REACTIVATION PROGRAM
SUMMARY OF REACTIVATION COSTS

Utility	Virgin GAC Cost ¢/kg	Virgin GAC Cost (¢/lb)	Reactivated GAC Cost ¢/kg	Reactivated GAC Cost (¢/lb)
Connecticut Water Co.	244.49	111.00	145.90	(66.24)
Danvers, Massachusetts	161.45	73.30	82.60	(37.50)
Lowell, Massachusetts	251.10	114.00	99.01	(44.95)

The experience gained from the regional reactivation program demonstrated that future reactivation work for other water utilities could be improved. A very apparent inefficiency of the regional program was the result of the batching type of reactivator operation. Once the spent GAC storage tank was emptied, the trailer truck containing the reactivated GAC returned to the utility to pick up another load of spent GAC. During the interim period of waiting for the truck to return, the reactivator was shut down. Before and after each shutdown, there was a period of about 6 hours (2 hours before and 4 hours after) required to adjust reactivator temperature. Through the course of this 6-hour period, the reactivator continued consuming fuel, power, water, etc., but there was no GAC being processed. This type of operation results in inefficiency in operation and higher operations costs.

It was concluded that in the future, this type of ineffiency can easily be resolved by utilizing two trailer trucks. Operation of the two trucks would ensure that the reactivator always had a constant flow of GAC thereby eliminating any need to shut the equipment down.

Shown on page 42 of this report is the cost analysis for reactivating the GAC at MWW. It should be noted that attempts to draw comparisons between MWW reactivation costs and the 3 utilities cost would be inaccurate. There are several reasons that make it difficult to draw such cost comparisons. First, the cost data developed for Manchester involved the reactivation of 841,401 kg (1,857,176 lbs) of GAC over a 10-month period versus reactivation of approximately 18,144 kg (40,000 lbs) of GAC over a period of about 75 hours for each utility. The difference in quantities and time periods make an economies of scale-type comparison invalid. Secondly, since the reactivation work for Manchester and the 3 utilities was performed during different time periods, the rate costs for items such as makeup carbon, labor, fuel, oil, electrical power, etc. also differed. Finally, the inefficiency resulting from the use of one trailer truck would also add difficulty to drawing comparisons between Manchester's reactivation costs and the regional utility reactivation costs.

TABLE 29

MANCHESTER WATER WORKS
REGIONAL REACTIVATION PROGRAM
DETAILS OF REACTIVATION WORK

1. UTILITY:		Connecticut Water Co.
2. TYPE & GRADE OF GAC:		Carborundum 8 x 30 (Lignite)
3. WEIGHT OF GAC REACTIVATED:		17,070 Kgs (37,632 Lbs)
4. VOLUME OF GAC REACTIVATED:		41.8 m^3 (1,476 ft^3)
5. START AND STOP OF FIRST RUN:		11:00 P.M., 11/16/81 to 5:00 P.M., 11/18/81
6. REACTIVATION PROCESS TIME FIRST RUN:		42 Hours
7. START AND STOP OF SECOND RUN:		6:00 P.M., 11/20/81 to 6:00 P.M., 11/21/81
8. REACTIVATION PROCESS TIME SECOND RUN:		36 Hours
9. ONE WAY DISTANCE TO UTILITY:		277 Kilometers (172 Miles)
10. ONE WAY TRAVEL TIME:		3.5 Hours
11. VOLUMETRIC REACTIVATION LOSSES*	FIRST RUN:	15.4%
	SECOND RUN:	15.6%
	AVERAGE:	15.5%
12. TOTAL VOLUMETRIC LOSSES‡	FIRST RUN:	22%
	SECOND RUN:	25%
	AVERAGE:	23.5%

*Volumetric losses resulting from reactivation only.
‡Volumetric losses resulting from reactivation and transportation.

TABLE 30

MWW REACTIVATION COSTS FOR
THE CONNECTICUT WATER CO.
NOVEMBER 16, 1981 TO NOVEMBER 21, 1981
BASED ON REACTIVATION OF 17,070 KGS (37,632 LBS) OF GAC

	Cost Item	Cost Per Kg	(Cost Per Lb)
A)	Makeup Carbon	57.50¢	(26.08¢)
B)	Labor for Reactivation	14.02	(6.36)
C)	Labor for Transportation	4.67	(2.12)
Cl)	Equipment for Transportation	11.84	(5.37)
D)	Labor for Lab	0.62	(0.28)
E)	Labor for Administration	8.49	(3.85)
F)	Parts and Service Calls	9.22	(4.18)
G)	Fuel Oil	6.79	(3.08)
H)	Electrical Power	2.49	(1.13)
I)	Water	5.11	(2.32)
J)	Lab Supplies	0.60	(0.27)
K)	Depreciation	3.31	(1.50)
L)	Overhead	21.38	(9.70)
	TOTAL COST	146.04¢	(66.24¢)

TABLE 31

MWW REACTIVATION COSTS FOR
THE CONNECTICUT WATER CO.
NOVEMBER 16, 1981 TO NOVEMBER 21, 1981
BASED ON REACTIVATION OF 17,070 KGS (37,632 LBS) OF GAC

	COST ITEM	TOTAL COST	TOTAL UNITS		UNIT RATES	
A)	Makeup Carbon	$ 9,816.	4,011 kgs	(8,843 lbs)	$ 2.45/kg	($1.11/lb)
B)	Labor for Reactivation	2,393.	308 man-hours		7.77/hr	
C)	Labor for Transportation	800.	103 man-hours		7.77/hr	
C1)	Equipment for Transportation	2,020.	554 km	(344 miles)	3.65/km	(5.87/mile)
D)	Labor for Lab	103.	13 man-hours		7.91/hr	
E)	Labor for Administration	1,449.	112 man-hours		12.94/hr	
F)	Parts and Service Calls	1,574.	N/A		1,574.00/utility	
G)	Fuel Oil	1,159.	3,816 L	(1,008 gals)	0.304/ L	(1.15/gal)
H)	Electrical Power	426.	6,000 KWH		0.071/KWH	
I)	Water	873.	5,453/m^3	(1,440,594 gals)	0.160/m^3	(0.606/ 1,000 gals)
J)	Lab Supplies	100.	N/A		100.00/utility	
K)	Depreciation	564.	78 hours		7.23/hr of reactivation	
L)	Overhead	3,654.	N/A		77% of labor	
	TOTAL	$ 24,931.				

N/A = Not Applicable

TABLE 32

EXPLANATION OF REACTIVATION COST ITEMS FOR THE CONNECTICUT WATER CO.

A) Makeup Carbon. Based on a total volumetric carbon loss of 23.5% experienced through one cycle of reactivation at a delivered cost to Connecticut of $2.45/kg ($1.11/lb).

B) Labor for Reactivation Operation and Maintenance. Based on a staff of 12 water treatment plant operators at an average wage of $7.77/hr. Approximately 308 man-hours of labor time was used to reactivate the Connecticut GAC.

C) Labor for Transportation. Based on 2 water treatment plant operators at an average wage of $7.77/hr used to load and off-load the GAC at the Manchester reactivator, and to assist loading and off-loading the GAC at the Connecticut water treatment facility. Approximately 103 man-hours of labor was used to transport the GAC.

C1) Equipment for Transportation. Based on a truck rental of $30.00/hr for the tractor and driver with a use of 46.25 hours, and $100.00/day for the trailer with a use of 6.3 days.

D) Labor for Laboratory Analysis to monitor quality control of the reactivation process. Based on a staff of one laboratory technician at a wage of $7.91/hr. Approximately 13 man-hours of labor time was used to perform the analysis.

E) Labor for Administration. Based on a staff of 2 engineers, chemist, secretary, purchasing agent and accountant. Approximately 112 man-hours of administrative labor was used during the Connecticut work.

F) Parts and Service Calls. Based on a total item cost of $4,722 divided equally by the 3 utilities that participated in the program for new parts, repair shop charges, and outside service calls. This item does not include MWW labor.

G) Fuel Oil. Based on an average of $0.304/liter ($1.15/gallon) of fuel oil and consumption of 42.4 liters/hr (11.2 gallons/hr) of reactivation or 6,959 Joules/gram (2,994 BTU/lb) of carbon.

H) Electrical Power. Based on an average cost of 7.10¢/KWH and a consumption of 48.6 KW/hr of operation for building and process energy, or 0.205 KWH/kg (0.093 KWH/lb) of GAC.

Table 32 (Continued)

I) Water. Based on a water production cost of \$0.160/m^3 (\$0.606/1,000 gals) and a consumption of 44.64 m^3/hr (11,792 gals/hr) of reactivator operation, or 0.189 m^3/kg (22.7 gals/lb) of GAC. Approximately 92% of the water was used for reactivation and 8% used for on-site transport.

J) Lab Supplies. Based on a total item cost of \$300., divided equally by the 3 utilities that participated in the program for supplies to perform reactivation process quality control analysis.

K) Depreciation. Based on the straight line depreciation calculations shown in Table 13, page 46.

L) Overhead. Based on a MWW overhead factor of 77% above labor costs that includes holidays, sick leave and fringe benefits. The total overhead for the overall MWW system is 305% and includes acquisition, treatment, distribution, and support services.

TABLE 33

MANCHESTER WATER WORKS
REGIONAL REACTIVATION PROGRAM
DETAILS OF REACTIVATION WORK

1.	UTILITY:	Danvers, Massachusetts
2.	TYPE & GRADE OF GAC:	Calgon Filtrasorb 300 Coal Base 8 x 30
3.	WEIGHT OF GAC REACTIVATED:	16,601 Kgs (36,000 Lbs)
4.	VOLUME OF GAC REACTIVATED:	43.55 m^3 (1,538 ft^3)
5.	START AND STOP OF FIRST RUN:	2:00 P.M., 12/01/81 to 7:00 P.M., 12/03/81
6.	REACTIVATION PROCESS TIME FIRST RUN:	41 Hours
7.	START AND STOP OF SECOND RUN:	4:45 P.M., 12/04/81 to 3:15 P.M., 12/05/81
8.	REACTIVATION PROCESS TIME SECOND RUN:	34.5 Hours
9.	ONE WAY DISTANCE TO UTILITY:	66 Kilometers (41 Miles)
10.	ONE WAY TRAVEL TIME:	1 Hour
11.	VOLUMETRIC REACTIVATION LOSSES*	FIRST RUN: 7.7% SECOND RUN: 11.1% AVERAGE: 9.4%
12.	TOTAL VOLUMETRIC LOSSES‡	FIRST RUN: 13.0% SECOND RUN: 9.8% AVERAGE: 11.4%

*Volumetric losses resulting from reactivation only.
‡Volumetric losses resulting from reactivation and transportation.

TABLE 34

MWW REACTIVATION COSTS FOR DANVERS, MASSACHUSETTS
DECEMBER 1, 1981 TO DECEMBER 5, 1981
BASED ON REACTIVATION OF 16,601 KGS (36,600 LBS) OF GAC

	Cost Item	Cost Per Kg	(Cost Per Lb)
A)	Makeup Carbon	18.43	(8.36¢)
B)	Labor for Reactivation	8.71	(3.95)
C)	Labor for Transportation	2.93	(1.33)
C1)	Equipment for Transportation	9.13	(4.14)
D)	Labor for Lab	0.62	(0.28)
E)	Labor for Administration	3.92	(1.78)
F)	Parts and Service Calls	9.48	(4.30)
G)	Fuel Oil	6.79	(3.08)
H)	Electrical Power	3.00	(1.36)
I)	Water	3.33	(1.51)
J)	Lab Supplies	0.60	(0.27)
K)	Depreciation	3.28	(1.49)
L)	Overhead	12.46	(5.65)
	TOTAL COST	82.68¢	(37.50¢)

TABLE 35

MWW REACTIVATION COSTS FOR
DANVERS, MASSACHUSETTS
DECEMBER 1, 1981 TO DECEMBER 5, 1981
BASED ON REACTIVATION OF 16,601 KGS (36,600 LBS) OF GAC

	COST ITEM	TOTAL COST	TOTAL UNITS		UNIT RATES	
A)	Makeup Carbon	$ 3,058.	1,892 kgs	(4,172 lbs)	$ 1.62/kg	($0.733/lb)
B)	Labor for Reactivation	1,447.	186 man-hours		7.77/hr	
C)	Labor for Transportation	485.	62.4 man-hours		7.77/hr	
C1)	Equipment for Transportation	1,518.	264 km	(164 miles)	5.75/km	(9.26/mile)
D)	Labor for Lab	103.	13 man-hours		7.91/hr	
E)	Labor for Administration	651.	50.3 man-hours		12.94/hr	
F)	Parts and Service Calls	1,574.	N/A		1,574.00/utility	
G)	Fuel Oil	1,127.	3,710 L	(980 gals)	0.304/L	(1.15/gal)
H)	Electrical Power	497.	7,000 KWH		0.071/KWH	
I)	Water	551.	3,442 m^3	(909,241 gals)	0.160/m^3	(0.606/ 1,000 gals)
J)	Lab Supplies	100.	N/A		100.00/utility	
K)	Depreciation	546.	75.5 hours		7.23/hr of reactivation	
L)	Overhead	2,068.	N/A		77%	
	TOTAL	$ 13,725.				

N/A = Not Applicable

TABLE 36

EXPLANATION OF REACTIVATION COST ITEMS FOR DANVERS, MASSACHUSETTS

A) Makeup Carbon. Based on a total volumetric carbon loss of 11.4% experienced through one cycle of reactivation at a delivered cost to Danvers of $1.62/kg ($0.7329/lb).

B) Labor for Reactivation Operation and Maintenance. Based on a staff of 12 water treatment plant operators at an average wage of $7.77/hr. Approximately 186 man-hours of labor time was used to reactivate the Danvers GAC.

C) Labor for Transportation. Based on 2 water treatment plant operators at an average wage of $7.77/hr used to load and off-load the GAC at the Manchester reactivator, and to assist loading and off-loading the GAC at the Danvers water treatment facility. Approximately 62.4 man-hours of labor was used to transport the GAC.

C1) Equipment for Transportation. Based on a truck rental of $30.00/hr. for the tractor and driver with a use of 29.5 hours, and $100.00/day for the trailer with a use of 6.3 days.

D) Labor for Laboratory Analysis to monitor quality control of the reactivation process. Based on a staff of one laboratory technician at a wage of $7.91/hr. Approximately 13 man-hours of labor time was used to perform the analysis.

E) Labor for Administration. Based on a staff of 2 engineers, chemist, secretary, purchasing agent and accountant. Approximately 50 man-hours of administrative labor was used during the Danvers work.

F) Parts and Service Calls. Based on a total item cost of $4,722 divided equally by the 3 utilities that participated in the program for new parts, repair shop charges, and outside service calls. This item does not include MWW labor.

G) Fuel Oil. Based on an average of $0.304/liter ($1.15/gallon) of fuel oil and consumption of 42.4 liters/hr (11.2 gallons/hr) of reactivation or 6,959 Joules/gram (2,994 BTU/lb) of carbon.

H) Electrical Power. Based on an average cost of 7.10¢/KWH and a consumption of 48.6 KW/hr of operation for building and process energy, or 0.205 KWH/kg (0.093 KWH/lb) of GAC.

Table 36 (Continued)

I) Water. Based on a water production cost of \$0.160/m^3 (\$0.606/1,000 gals) and a consumption of 44.64 m^3/hr (11,792 gals/hr) of reactivator operation, or 0.189 m^3/kg (22.7 gals/lb) of GAC. Approximately 92% of the water was used for reactivation and 8% used for on-site transport.

J) Lab Supplies. Based on a total item cost of \$300., divided equally by the 3 utilities that participated in the program for supplies to perform reactivation process quality control analysis.

K) Depreciation. Based on the straight line depreciation calculations shown in Table 13, page 46.

L) Overhead. Based on a MWW overhead factor of 77% above labor costs that includes holidays, sick leave and fringe benefits. The total overhead for the overall MWW system is 305% and includes acquisition, treatment, distribution, and support services.

TABLE 37

MANCHESTER WATER WORKS
REGIONAL REACTIVATION PROGRAM
DETAILS OF REACTIVATION WORK

1. UTILITY:		Lowell, Massachusetts
2. TYPE & GRADE OF GAC:		Westvaco WVW 8 x 30 Coal Base
3. WEIGHT OF GAC REACTIVATED:		19,125 Kgs (42,163 Lbs)
4. VOLUME OF GAC REACTIVATED:		33.1 m^3 (1,170 ft^3)
5. START AND STOP OF FIRST RUN:		4:00 P.M., 12/09/81 to 8:00 P.M., 12/11/81
6. REACTIVATION PROCESS TIME FIRST RUN:		40 Hours
7. START AND STOP OF SECOND RUN:		3:00 A.M., 12/15/81 to 6:15 P.M., 12/16/81
8. REACTIVATION PROCESS TIME SECOND RUN:		27.15 Hours
9. ONE WAY DISTANCE TO UTILITY:		53.1 Kilometers (33 Miles)
10. ONE WAY TRAVEL TIME:		45 Minutes
11. VOLUMETRIC REACTIVATION LOSSES*	FIRST RUN:	12.5%
	SECOND RUN:	15.3%
	AVERAGE:	13.9%
12. TOTAL VOLUMETRIC LOSSES‡	FIRST RUN:	14.0%
	SECOND RUN:	16.6%
	AVERAGE:	15.3%

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*Volumetric losses resulting from reactivation only.
‡Volumetric losses resulting from reactivation and transportation.

TABLE 38

MWW REACTIVATION COSTS FOR LOWELL, MASSACHUSETTS
DECEMBER 9, 1981 TO DECEMBER 16, 1981
BASED ON REACTIVATION OF 19,125 KGS (42,163 LBS) OF GAC

	Cost Item	Cost Per Kg	(Cost Per Lb)
A)	Makeup Carbon	38.44¢	(17.44¢)
B)	Labor for Reactivation	10.23	(4.64)
C)	Labor for Transportation	2.84	(1.29)
C1)	Equipment for Transportation	6.83	(3.10)
D)	Labor for Lab	0.53	(0.24)
E)	Labor for Administration	4.37	(1.98)
F)	Parts and Service Calls	8.22	(3.73)
G)	Fuel Oil	5.34	(2.42)
H)	Electrical Power	2.49	(1.13)
I)	Water	2.89	(1.31)
J)	Lab Supplies	0.53	(0.24)
K)	Depreciation	2.54	(1.15)
L)	Overhead	13.84	(6.28)
	TOTAL COST	99.09¢	(44.95¢)

TABLE 39

MWW REACTIVATION COSTS FOR
LOWELL, MASSACHUSETTS
DECEMBER 9, 1981 TO DECEMBER 16, 1981
BASED ON REACTIVATION OF 19,125 KGS (42,163 LBS) OF GAC

	COST ITEM	TOTAL COST	TOTAL UNITS		UNIT RATES	
A)	Makeup Carbon	$ 7,354.	2,926 kgs	(6,451 lbs)	$ 2.51/kg	($1.14/lb)
B)	Labor for Reactivation	1,958.	252 man-hours		7.77/hr	
C)	Labor for Transportation	543.	69.9 man-hours		7.77/hr	
C1)	Equipment for Transportation	1,308.	106.2 km	(66 miles)	12.32/km	(19.82/mile)
D)	Labor for Lab	103.	13 man-hours		7.91/hr	
E)	Labor for Administration	833.	64.4 man-hours		12.94/hr	
F)	Parts and Service Calls	1,574.	N/A		1,574.00/utility	
G)	Fuel Oil	1,021.	3,361 L	(888 gals)	0.304/L	(1.15/gal)
H)	Electrical Power	476.	6,704 KWH		0.071 KWH	
I)	Water	551.	3,442 m^3	(909,241 gals)	0.160 m^3	(0.606/ 1,000 gals)
J)	Lab Supplies	100.	N/A		100.00/utility	
K)	Depreciation	486.	67.25 hrs		7.23/hr of reactivation	
L)	Overhead	2,646.	N/A		77%	
	TOTAL	$18,953.				

N/A = Not Applicable

TABLE 40

EXPLANATION OF REACTIVATION COST ITEMS FOR LOWELL, MASSACHUSETTS

A) Makeup Carbon. Based on a total volumetric carbon loss of 15.3% experienced through one cycle of reactivation at a delivered cost to Lowell of $2.51/kg ($1.14/lb).

B) Labor for Reactivation Operation and Maintenance. Based on a staff of 12 water treatment plant operators at an average wage of $7.77/hr. Approximately 252 man-hours of labor time was used to reactivate the Lowell GAC.

C) Labor for Transportation. Based on 2 water treatment plant operators at an average wage of $7.77/hr used to load and off-load the GAC at the Manchester reactivator, and to assist loading and off-loading the GAC at the Lowell water treatment facility. Approximately 69.9 man-hours of labor was used to transport the GAC.

C1) Equipment for Transportation. Based on a truck rental of $30.00/hr for the tractor and driver with a use of 22.5 hours, and $100.00/day for the trailer with a use of 6.3 days.

D) Labor for Laboratory Analysis to monitor quality control of the reactivation process. Based on a staff of one laboratory technician at a wage of $7.91/hr. Approximately 13 man-hours of labor time was used to perform the analysis.

E) Labor for Administration. Based on a staff of 2 engineers, chemist, secretary, purchasing agent and accountant. Approximately 64 man-hours of administrative labor was used during the Lowell work.

F) Parts and Service Calls. Based on a total item cost of $4,722 divided equally by the 3 utilities that participated in the program for new parts, repair shop charges, and outside service calls. This item does not include MWW labor.

G) Fuel Oil. Based on an average of $0.304/liter ($1.15/gallon) of fuel oil and consumption of 42.4 liters/hr (11.2 gallons/hr) of reactivation or 6,959 Joules/gram (2,994 BTU/lb) of carbon.

H) Electrical Power. Based on an average cost of 7.10¢/KWH and a consumption of 48.6 KW/hr of operation for building and process energy, or 0.205 KWH/kg (0.093 KWH/lb) of GAC.

Table 40 (Continued)

I) Water. Based on a water production cost of \$0.160/m^3 (\$0.606/1,000 gals) and a consumption of 44.64 m^3/hr (11,792 gals/hr) of reactivator operation, or 0.189 m^3/kg (22.7 gals/lb) of GAC. Approximately 92% of the water was used for reactivation and 8% used for on-site transport.

J) Lab Supplies. Based on a total item cost of \$300., divided equally by the 3 utilities that participated in the program for supplies to perform reactivation process quality control analysis.

K) Depreciation. Based on the straight line depreciation calculations shown in Table 13, page 46.

L) Overhead. Based on a MWW overhead factor of 77% above labor costs that includes holidays, sick leave and fringe benefits. The total overhead for the overall MWW system is 305% and includes acquisition, treatment, distribution, and support services.

BIBLIOGRAPHY

APHA-AWWA-WPCF. 1975. Standard Methods for the Examination of Water and Wastewater, 14th Edition. American Public Health Association, Washington, D.C. 1976

Ireland, John. 1983. Statistical Analysis of Breakthrough Curves. Appendix C. Final Report. USEPA Grant No. CR805371.

Lykins, B., Griese, M., and Mills, D. 1981. Chlorine Dioxide Disinfection and Granular Activated Carbon Adsorption. Environmental Protection Agency.

McGinnis, F.K., and Horwitz, G. 1981. Effects on Thermal Regeneration on Activated Carbon Properties. American Chemical Society.

McGinnis, F.K., and Inhoffer, W.R. 1980. Regenerating Granular Activated Carbon at Passaic Valley. American Water Works Association.

Miller, R., Hartman, D., and DeMarco, J. 1981. Cincinnati Full Scale Research Project with Granular Activated Carbon. American Water Works Association.

Symons, J., Stevens, A., Clark, R., Geldreich, E., Love, T., and DeMarco, J. 1981. Treatment Techniques for Controlling Trihalomethanes in Drinking Water. Environmental Protection Agency.

U.S. EPA Environmental Monitoring and Support Laboratory. 1979. The Analysis of Trihalomethanes in Drinking Water by Liquid/ Liquid Extraction. Method 501.2 Cincinnati, Ohio.

U.S. EPA Environmental Monitoring and Technical Support. 1978. Manual for the Interim Certification of Laboratories Involved in Analyzing Public Drinking Water Supplies: Criteria and Procedures. EPA 600/88-78, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA Technology Transfer. 1973. Process Design Manual for Carbon Adsorption. EPA 625/1-71-002a, U.S. Environmental Protection Agency.

APPENDIX A

ANALYTICAL AND GAC LOSS PROCEDURES

Trihalomethanes

The analytical procedure adopted for running trihalomethane was based on "The Analysis of Trihalomethanes in Drinking Water by Liquid/Liquid Extraction", Method 501.2 developed by the US Environmental Monitoring and Support Laboratory, Cincinnati, Ohio, May 15, 1979. This publication describes the basic chromatographic analytical procedures and principles utilized in our analysis for trihalomethanes.

Apparatus and Reagents

Gas Chromatograph: Perkin-Elmer Model Sigma I with nickle-63 electron capture detector.

The Perkin-Elmer Sigma I gas chromatograph was selected because of its integrative capacity as well as the reputation of having a very good technical support in our region.

Glass Column: 2 mm ID x 2 m long, glass packed with 10% squalene on chrom-W-AW (80/100 mesh), operated at 55°C with 30 mL per minute flow through the column.

Carrier Gas: 95% argon, 5% methane ECD grade.

Extraction Vessels: 13 mm x 100 mm borosilicate glass test tubes with polyethylene stoppers.

Sampling Containers: 40 mm glass, screwed top bottles with teflon faced silicone septa.

Micro-Syringes 5 uL, 10 uL, and 50 uL.

Pipettes: 5 mL and 1 mL, Class A.

Glass Stoppered Volumetric Flasks: 10 mL and 100 mL, Class A.

Analytical Balance: ±0.0001 gm for gravimetric makeup of standards.

Standard Storage Containers: 15 mL amber screw top, septum bottles with teflon faced silicon septa.

Extraction Solvent: Interference-free methylcyclohexane.

Methanol: ACS reagent grade for standards.

Free and Combined Reducing Agent: Sodium thiosulfate ACS reagent grade.

Standards: Chloroform ($CHCl_3$), Bromodichloromethane ($CHBrCl_2$), Dibromochloromethane ($CHBr_2Cl$), (Bromoform ($CHBr_3$). ACS reagent grade, 1-1-1 Trichloroethane used as a reference peak.

Organic-Free Water

Procedure

Standardization of the chromatograph was accomplished through the use of external standards developed according to the procedures specified in the 1979 USEPA Method 501.2. In practice, a sample containing known quantities of all trihalomethanes was run at least once a week, solvent blanks and unchlorinated samples were run daily and unknown samples from EPA's Monitoring and Support Laboratory in Cincinnati were run quarterly.

Five ml of the water quality sample collected during the study were extracted in one milliliter of methylcyclohexance in a polyethylene stoppered test tube. This mixture was vigorously shaken for at least 30 seconds. One microliter of this extract was then injected into the gas chromatograph in an isothermal mode with an injection temperature of 150°C, oven temperature of 55°C, and detector temperature of 300°C. Response factors calculated from known external standards were used directly in the integration phase to produce an output designating concentrations of $CHCl_3$, $CHBrCl_2$, $CHBr_2Cl$, $CHBr_3$. The isothermal program was 12 minutes long which allowed for the complete elution of all the trihalomethanes including bromoform which had the longest relative retention time at 10.6 minutes. Chromatographic temperatures as well as column flow rates and extraction ratios were developed empirically to give the best precision and accuracy.

Instantaneous Trihalomethanes

In the ITHM analysis, samples were collected with no air space in 40 mL, screw top, teflon septaed vials. The vials contained sodium thiosulfate before collection which provided an instantaneous quenching of the free chlorine which produces trihalomethanes. Samples were then delivered to the laboratory and kept refrigerated at 2°C until analysis. For analysis, these samples were warmed to room temperature and then extracted by the procedures described above for trihalomethanes.

Trihalomethane Formation Potential

The determination of maximum trihalomethane formation potential was examined at different temperatures and for 2 different lengths of time. In order that temperature and time would be the only variables, a 1 liter sample of water was collected in a organic free glass bottle. Immediately after collection, the 1 liter samples were refrigerated until their temperatures were from 2° to 10°C below the ambient temperature of the water treatment plant processed water. This preliminary cooling ensured that the temperature of the samples during the chlorination and pH adjustment never exceeded the temperature of the ambient water bath. At the same time, another sample was also collected in the manner described above for ITHM.

A chilled 250 mL sample was placed on a magnetic stirrer with a pH electrode emersed in the sample. Predetermined amounts of sodium hypochlorite were then added which would give a free chlorine residual of at least 5 mg/L after a period of 7 days at the maximum water temperature of 28.5°C. Immediately after the addition of the sodium hypochlorite, the pH of the sample was dropped to 8.0 ± .2 by the addition of 0.1 normal hydrochloric acid. The sample was then poured into 4, 40 milliliter teflon septa sealed vials with no air bubbles. Two of the bottles were immediately placed in the ambient temperature water bath, and the other 2 vials were placed in the 28.5°C water bath. This temperature was approximately the maximum temperature reached by the treated water in our distribution system. After a period of 3 days, 1 vial in each of the water baths was treated with enough sodium thiosulfate to quench the remaining free chlorine. The other 2 vials remained in the water baths for a total of 7 days, and then at this time, they were also quenched with sodium thiosulfate. After quenching, samples were stored at approximately 2°C until analysis by methods described in the Trihalomethane section of this Appendix.

Total Organic Carbon

Apparatus and Reagents

Dohrmann DC-54 Low Total Organic Carbon Analyzer System:	Oxidation of all soluable organic carbon to CO_2 by exposure of the sample to ultraviolet radiation in the presence

of persulfate and acid with the subsequent reductive pryolysis of all organic carbonaceous gasses produced to methane by the use of a rhodium catalyst and eventual flame ionization detection with a linear response to methane. Through a timed sequence of events, purgeable organic carbon (POC) or volatile organic carbon, and nonpurgeable organic carbon (NPOC) content is determined.

Glass Spargers:	POC-2, NPOC
Pipettes:	1 mL graduated Mohr pipette, 10 mL volumetric pipette, Class A.
Sample Vials:	40 mL screw top teflon septaed vials, cleaned and baked at 170°C for 2 hours.
Helium:	0 grade (99.95% pure)
Compressed Air:	0 grade
Hydrogen:	0 grade
Reductive Pyrolysis Catalyst:	Rhodium
Inorganic Carbon Scrubber:	Lithium hydroxide
Sample Reagent:	Potassium persulfate ($K_2S_2O_8$) reagant grade, and concentrated (85%) phosphoric acid (H_3PO_4) reagant grade.
Carbon Standard:	Potassium hydrogen phthalate (KHP;$C_8H_5O_4K$), reagent grade.
Inorganic Carbon Standard:	Sodium carbonate (Na_2CO_3), reagent grade.
Volumetric Flasks:	500 and 100 mL, Class A.
Organic Free Water:	Less than 60 ug TOC
Standard Storage Containers:	Screw top, 500 mL amber glass bottles with teflon lined caps.

Reagent Storage
Container: 100 mL amber glass screw top bottle with teflon lined cap.

Procedure

The Dohrmann TOC Analyzer is an extremely sensitive, stable instrument, capable of very repeatable results. Prior to running the aqueous samples, a system blank was run for baseline TOC, this was accomplished by flushing the system with organic free water, i.e., water exposed to ultraviolet radiation for 20 minutes and then purged with helium gas. Standardization of the instrument was accomplished through the use of known solutions of KHP and because of the stability of the unit, KHP standards were used on a weekly basis with system blanks used as a daily indication of the instrument's performance. The effectiveness of inorganic CO_2 removal by the lithium hydroxide scrubber was measured through the use of a sodium carbonate standard.

Forty mL of sample were collected in clean, heat treated vials and analyzed immediately for TOC by the following procedure. Ten milliliters of the aqueous sample were introduced into the POC_2 sparger volumetrically and then acidified with 0.5 milliliters of the potassium persulfate/phosphoric acid sample reagent. The sample was purged with helium at 120 milliliters/minute for 3 minutes which removed purgeable organic carbon and transferred it through a lithium hydroxide column for removal of inorganic CO_2. After the sample was purged in the POC-2 sparger, it was exposed to ultraviolet radiation for a period of 3-1/2 minutes and then transferred to the NPOC sparger for additional purging by the helium gas at 120 mm/min for 5-1/2 minutes. The helium from the POC and NPOC spargers was passed through the pyrolysis zone (790°C) and in the presence of the catalyst rhodium and with the addition of hydrogen gas, the oxidized soluable organic carbon formed methane which was detected by the Flame Ionization Detector and through integration, displayed as TOC in ug/L. The system blank was then subtracted from the displayed value for the true TOC level as ug/L. Duplicate analyses were performed for every sample and system blanks were run after samples containing greater than 2.5 ug/L TOC to avoid contamination of subsequent samples.

Ambient Temperature

A continuously flowing covered water bath (using plant processed water) was checked on a daily basis for temperature by emersion of a glass mercury thermometer with a range of -1°C to 51°C in 0.1° increments. The thermometer was checked montly against a certified Taylor permafused edged stem thermometer and temperature readings were corrected for any differences.

Apparent Color

In order to provide a fast, repetitive and nonsubjective means of determining the color of low turbidity waters, a spectrophotometric instrumental procedure was developed by David Paris of the MWW. The procedure is for the determination of apparent color where neither filtration, centrification of pH adjustment are utilized and, therefore, the resultant color includes not only the color (true color) due to substances in solution but that due to suspended matter. A wavelength of 401 nanometers and a lightpath length of 10 centimeters were determined to give the optimum readings on the spectrophotometer, and color standards made from potassium chloroplatinate were used for spectrophotometric comparison.

Apparatus and Reagents

Bausch and Lomb Spectronic 70 having 10 cm cylindrical adsorption cuvettes and operated at a wavelength of 401 nanometers.

Color Standards:	Potassium chloroplatinate (K_2PtCl_6) 0 to 40 units, prepared according to Method 204A of Standard Methods "Color/Visual Comparisons Method", 14th Edition.
Deionized:	Activated carbon filtered distilled water

Procedure

Potassium chloroplatinate color standards with values of 1, 3, 5, 10, 15, 25, 30 and 35 were prepared, and a distilled water blank were used to zero the instrument. Absorbance values were obtained using the 10 centimeter cylindrical cuvettes and a wavelength of 401 nanometers. The results were then plotted to obtain a standard curve which was verified with the potassium chloroplatinate standards every 6 months. The apparent color of the water was determined by filling a cuvette with the appropriate aqueous sample and comparing it to a distilled water blank. The apparent color was then determined from the standard curve and recorded as apparent color to the nearest whole number. In cases of colors exceeding 30 units, dilutions with distilled water were performed with the appropriate multiplication factors used for calculating results. As the aqueous samples analyzed were primarily low turbidity samples (less than 0.5 NTU) no attempt was made to distinguish between apparent and true color.

Turbidity

Apparatus and Reagents

Hach 2100A Nephlometric Turbidmeter

Turbidity Standard: Hach 0.61 NTU chlorobenzene in sealed cuvette.

Turbidity Standard: AMCO Standards International, Inc. - AEPA-1 Turbidity Standards - 1.0 NTU and 5.0 NTU.

Turbidity Free Water:

Procedure

The Hach 2100A turbidimeter was calibrated on a daily basis using the pre-made Hach 0.61 NTU chlorobenzene standard and also checked monthly with AMCO AEPA standards. Aqueous samples were collected and analyzed immediately.

pH

Apparatus and Reagents

pH Meter: Corning, Model #125

pH Electrode: Cole-Palmer, Model #4991-40 combination Ag/AgCl electrode

Magnetic Bar Stirrer

pH Standards: pH buffer 4, pH buffer 7

Deionized: Demineralized water

Procedure

The pH meter was calibrated on a daily basis using fresh certified buffer solution of a pH of 4 and a pH of 7. The temperature of the aqueous samples was measured and temperature compensation was adjusted to the temperature of the solutions. The aqueous samples were gently mixed to equilbrium.

Chlorine Residual (Free Available)

Apparatus and Reagents

Amperometric Titrimeter: Fisher Chlorine Titrimeter, Model #393

Hellige DPD Colorimetric Comparator for Chlorine: Model #607-A26

Phenylarsine Oxide Solution 0.00564 Normal:	Certified
Phosphate Buffer Solution, pH 7:	Certified
N,N-diethyl-p-Phenylene-diamine (DPD):	Hellige DPD #1 tablets

Procedure

Aqueous samples were collected on a daily basis and analyzed immediately for free available chlorine using a Hellige Colorimetric comparator and Hellige DPD #1 tables for free available chlorine. Samples were also checked weekly for free available chlorine using the amperometric titration method with a standard phenylarsine oxide solution.

Total Coliform

The procedure for total coliform analysis was adopted from Method 909A of Standard Methods, 14th Edition. Aqueous samples were collected in 125 milliliter borosilicate glass bottles containing sodium thiosulfate. The bottles were baked at 170°C for 2 hours to ensure sterility. One hundred milliliters of the aqueous sample (or a dilution of the sample ensuring 80 to 100 total coliform colonies per plate) was filtered through a sterile 0.45 micron membrane filter which was then placed on m-Endo media containing agar, and then incubated at 35° ±0.5° for 24 hours ±2 hours. All colonies showing the typical brilliant golden green sheen were then confirmed in gas tubes containing laurel sulfate broth and brilliant breen lactose broth. All quality control procedures as described in "Manual for the Interim Certification of Laboratories Involved in Analyzing Public Drinking Water Supplies" were followed.

Standard Plate Count

The procedure followed for standard plate count analysis was Method 907 of Standard Methods, 14th Edition. Aqueous samples were collected in the same manner described above for total coliform analysis. One milliliter of the sample was placed in a sterile petri dish and 10 to 12 mL of melted (44°C to 46°C) Standard Methods Agar media was placed in immediately after sample introduction and the contents of the dish were swirled to ensure even dispersal of the sample. The petri dish was then incubated for 48 hours ±3 hours at 35.0°C, and then all colonies were counted using a Quebec Colony Counter.

GAC Analyses: Apparent Density and Iodine Number

Analysis of the GAC was accomplished by following the test procedures described in Appendix B of "Process Design Manual for Carbon Adsorption", USEPA publication #625/1-71-002a, October 1973.

Apparent Density

Apparatus and Reagents

Drying Oven:	
Vibrator Feeder:	Feed rate 100 mL of GAC/100-133 seconds
Cylinder:	100 ml ASTM graduated cylinder
Stop-Watch:	
Analytical Balance:	±0.001 gm

Procedures

The GAC samples were dried at 110°C for 3 hours and then placed in the vibrator feeder. The feeder speed was adjusted so that it took 100 - 133 seconds for 100 mL of GAC to be collected in a pre-weighed 100 ml ASTM graduated cylinder. The GAC was weighed and A.D. calculated from the weight of 100 mL of GAC.

Iodine Number

Apparatus and Reagents

Sample Splitter:	Humboldt Riffle
Spex-Mixer Mill:	#8000 and #8001 Grinding Vials
Hydrochloric Acid Solution:	5% by weight
Sodium Thiosulfate:	0.1 normal, standardized with 0.100 normal potassium biniodate ($KH(IO_3)_2$).
Iodine Solution:	Standardized with 0.100N sodium thiosulphate.
Filter Paper:	Whatman Folded No. 2V 10.6 cm

Procedure

A representative dried 5.5 gm sample of GAC was ground for 70 seconds in the Spex-Mixer Mill and then 1.0 gm was analyzed for iodine number by following the procedure detailed in the previously mentioned reference, i.e., Appendix B of "Process Design Manual for Carbon Adsorption". I.N. was calculated by determining the normality of a standardized iodine solution after the solution had been shaken for 30 seconds with 1,000 gm of GAC.

Decolorizing Index

Apparatus and Reagents

Sample Splitter:	Humboldt Riffle
Spex-Mixer Mill:	#8000 and #8001 Grinding Vials
Klett-Summerson Colorimeter:	#54 green filter and 10 ml adsorption tubes.
Blackstrap Mollases:	(Westvaco Standard)
Anhydrous Disodium Phosphate:	
Supercel Filter Aid:	
Phosphoric Acid:	
Standard D.I. Carbon:	(Westvaco)

Procedure

A representative dried 5.5 gm sample of GAC was ground for 70 seconds in the Spex-Mixer Mill and then 0.460+ 0.001 grams of the dried ground carbon was analyzed for D.Ī. by following the procedure detailed in the previously mentioned reference, i.e., Appendix B of "Process Design Manual for Carbon Adsorption". The D.I. of the GAC sample was determined from a standard curve of known weights of standard carbon and their known Assigned Decolorizing Index Number against these standard carbon Klett-Summerson readings for the molasses solutions.

Sieve Analysis (Dry)

Apparatus

Sample Splitter:	Humboldt Riffle
Ro-Tap:	Sieve Shaker
Sieves:	U.S. Standard A.S.T.M. Sieves Nos. 6, 8, 12, 16, 20, 30, 40, Pan.
Balance:	±0.01 gm

Procedure

A representative 100.00 gm of GAC were placed in the Ro-Tap Sieve Shaker equipped with sieves #6, 8, 12, 16, 20, 30, 40 and a receiving pan. After the sieve shaker was operated for 3 minutes, the GAC retained on each sieve and in the pan was weighed to the nearest one-hundredth of a gm and the percent retained for each sieve calculated.

Abrasion Number and Mean Particle Diameter

Apparatus

Sample Splitter: Humboldt Riffle

Ro-Tap: Sieve Shaker

Sieves: U.S. Standard A.S.T.M. Sieves No. 6, 8, 12, 16, 20, 30, 40 and receiving pan.

Special Hardness Pan and Half Height Blank Pan:

Balance: ±0.01 gm

Procedure

A representative 100.00 gm sample of GAC was treated as for the dry sieve analysis previously described, only the sieve-shaker time was increased to 10 minutes. The GAC retained on each sieve was weighed and saved, and the mean particle diameter calculated following the procedure previously referenced above, i.e., Appendix B of "Process Design Manual for Carbon Adsorption". The weighed fractions of the original sample were recombined and placed in the special abrasion pan assembly with 10-1/2 inch diameter and 10-3/4 inch diameter steel balls and shaken on the Ro-Tap machine for 20 minutes. The GAC sample was then again Ro-Tap sieve shaken using the original screens and the mean particle diameter following the abrasion treatment was calculated. The Abrasion Number for the GAC sample was calculated as the final mean particle diameter divided by the original mean particle diameter, times 100.

Mass Balance Loss Procedure #1 (By Westvaco)

Process Flow and Discussion

A process flowsheet for the carbon reactivation system at Manchester is given in Figures A-1 and A-2. The mass balance procedure entails determination of the weight of GAC leaving the reactivation system. Spent GAC including fines generated during carbon transport is fed to the spent carbon tank (ST-1). Part of the smaller fines appear in water overflow stream ① during this transfer operation. During normal operation, this transfer would occur about 2 to 3 hours each day. Otherwise, stream ① flow would be a low water flow set to keep ST-1 full of water (a water level device maintains a constant water level but there the device is set up so that there is always some water flow). Therefore, except for the daily 2 to 3 hours of spent carbon transfer, stream ① would not be expected to contain carbon fines. Any carbon loss procedure should not have carbon transfer during the test to avoid this non steady state of carbon fines.

The spent carbon is then melted from ST-1 through a rotary valve (RV-1) and is educted via eductor (ED-1) to the dewatering screw (DS-1). The transport and excess water overflows from DS-1 to drain via stream ② . The water stream contains some fines generated by carbon transport to ST-1 by RV-1, Ed-1, by carbon transport piping from ED-1 to DS-1, and by DS-1.

The dewatered spent carbon is fed to the fluid-bed dryer reactivator and then discharged to the quench tank (QT-1) where the reactivated carbon is cooled and wetted for transport to the reactivated carbon storage tank (ST-2). The water overflow stream ③ contains some fines generated during the quench operation. This flow is irregular in that an overflow surge tank periodically cuts on and off, but the fines content of this stream is expected to be neglible.

The reactivated carbon is educted from QT-1 via an eductor (ED-2) to the reactivated carbon storage tank (ST-2). The transport water overflows from ST-2 to drain via stream ⑤ . The water stream contains some fines generated in QT-1, by ED-2, and by carbon transport piping from ED-2 to ST-2. The rest of the fines from these sources would be educted back to the adsorber.

The off-gas from the reactivator passes through a tray scrubber (SR-1) before being discharged to the atmosphere. The inlet gas to SR-1 contains fines generated by attrition in the fluid-bed and fines elutriated from the carbon but generated by other processing steps. Those steps include fines generated by carbon transport to ST-1, by RV-1, by ED-1, by carbon transport piping from ED-1 to DS-1, and by DS-1. The inlet gas also contains CO_2 which originates from gasification of the parent carbon. The majority of the CO_2 which originates from gasification of the parent carbon. The majority of the CO_2 originates from combustion of the fuel oil and from gasification of the fixed carbon which originates from the adsorbate on the spent carbon. Stream ⑥ discharged from SR-1 contains those fines not removed by scrubbing and the CO_2.

All carbon weight loss then must either show up in 1 of the 5 water streams, in the gas stream or it must accumulate within the system. Even at 2% carbon loss, the accumulation would be 10 lbs/hr which would quickly plug lines. As such, the principal assumptions in the mass balance procedure are that the reactivation system is at steady state and there is no accumulation of fines in the reactivator. Steady state needs to be defined. In this case, steady state will be when the rotary valve feeder (RV-1) is set at the design rate of 500 lbs of carbon/hr with a constant input of fuel oil to achieve a constant reactivation temperature ($\pm 200^{\circ}$F). This has been found to be sufficient to produce specification reactivated carbon with an IN $>$ 850 and a DI $<$ 10. Any variations in steady state are normally reflected in reactivated carbon variations of IN or DI (IN $<$ 850 and DI $>$ 6 at least for the first reactivation cycle).

Carbon Fines Discharge Rate Determination

When the system is at steady state, sampling of the off-gas discharge stream and of the combined water discharge streams (stream ⑦ , Figure A-2) from the carbon reactivation system begins. Determination of the carbon fines discharge rate from each stream will be discussed separately.

Off-Gas - Carbon Fines Rate

EPA procedure (40 CFR60 Appendix A, Methods 1 to 5) utilizing a RAC Staksampler, will be followed to determine the total particulate emission rate discharged from the reactivator. The EPA procedure as given detects the total particulate rate, so for the current analysis, all this particulate is assumed to be carbon fines. In this case, the carbon fines rate, ER_1 (lbs/hr) emitted from the off-gas is obtained.

A sampling frequency for the off-gas of twice/24 hr period is recommended.

Water Discharge - Carbon Fines Rate

The procedure for determination of the carbon fines rate in the water discharge from the reactivation system is:

1. Measure the water discharge rate by collecting a quantity of water in a 5 gallon pail over a time interval, Δt (seconds). Weigh the bucket of water and subtract the tare weight of the bucket to get the weight of water

W_{H_2O} (pounds).

Calculate the water rate:

$$H_2O \text{ rate}, \frac{l}{\text{Min}} = \left[\frac{W_{H_2O}}{\Delta t}\right]\left[\frac{60 \text{ Sec}}{\text{Min}}\right]\left[\frac{\text{Gal.}}{8.34 \text{ Lbs}}\right]\left[3.785\ \ell/g\right]$$

$$= 22.25\ \ell/\text{Min } W_{H_2O}/\Delta t$$

2. Take a one liter sample of the water discharge stream. Filter the water sample through a FH 0.5 micron filter with a known dry weight, W_{FP} (grams). Dry the filter paper plus carbon fines to get a dry weight, W_T (grams). Measure the volume of the filtrate, V_{FIL} (liters). Calculate the carbon fines concentration:

$$\text{C. Fines } (\text{gm}/\ell) = \left(\frac{W_T - W_{FP}}{V_{FIL}}\right) = 1.00 \text{ gm/L}$$

3. From these 2 inputs of the water rate and the carbon fines concentration, the carbon fines rate, ER_2 (kg/hr) emitted from the system via the water stream is calculated:

   ER_2 = Carbon Fines Rate, kg/hr

   The sampling and rate determinations are made while the system is operating at steady state. A sample and rate check is recommended at a frequence of once per hour.

Carbon Loss Determination

With the carbon fines discharge rates from above and the spent carbon feed rate to the reactivator, a carbon loss procedure can be determined. Before discussing the calculational procedure, the method of carbon rate determination should be given.

Carbon Rate Determination

The spent carbon feed rate is determined independent of the operation of the fluid-bed reactivator. Rate checks are made with carbon flow through the carbon loop including spent carbon storage tank (ST-1), rotary feed valve (RV-1), spent carbon eductor (ED-1) and dewatering screw (DS-1). The carbon discharged from the dewatering screw is collected manually over a specified period of time when either recycled to ST-1 or to another storage tank (but, normally to ST-1). The wet carbon rate check is combined with moisture analysis and A.D. of the spent carbon to calculate a dry volumetric feed rate.

Specifically, the method involves setting RV-1 at a measured shaft speed, W (rpm), then collecting spent carbon passed through RV-1 via carbon discharged from DS-1. The carbon collected over a known time period, Δt rate (minutes) is weighed to get a total wet weight, W_{SC} kg. The moisture content of the carbon collected is determined as P_{SC} (weight percent), and the A.D. on a dry basis in determined as AD_{SC} (kg/M^3). The volumetric feed rate at the shaft speed W is calculated as:

$$R_V = \text{Spent Carbon Feed Rate, } M^3/hr = \frac{W_{SC}\ (100P_{SC})}{t\ rate\quad (AD_{SC})} \left(\frac{60\ Min.}{Hr.}\right)$$

$$= 0.6 \left(\frac{W_{SC}}{t\ rate}\right)\left(\frac{P_{SC}}{AD_{SC}}\right)$$

This procedure is repeated for different shaft speeds until a calibration curve of speed carbon feed rate versus rotary valve shaft speed has been obtained for the valve operating under the certain set of conditions. For instance, water agitation in the cone section of ST-1 or the throat section of RV-1 appeared to affect the output of RV-1. As such, the rotary valve should be calibrated under the operating conditions expected.

With the calibration curve available and the reactivation system operating, the carbon feed rate is determined as follows:

1. A sample of spent carbon feed to the fluid-bed dryer is taken.

2. The sample is dried and the A.D. determined. The volatile content P_{VOL} (weight percent) of the dried carbon is also determined.

3. The shaft speed, W, of the rotary valve (RV-1) is determined.

4. From the calibration curve for that shaft speed, a spent carbon feed rate, R_V (M^3/hr) is obtained.

5. The carbon feed rate on a mass flow adsorbate free basis is then calculated:

$$R_W = \begin{array}{l}\text{Spent Carbon Feed Rate}\\ \text{(kg adsorbate free carbon/hour)}\end{array} = \left(R_V\right)\left(A_D\right)\left[\frac{100-(P_{VOL}/0.9)}{100}\right]$$

In the determination of the spent carbon feed rate on a free, mass flow basis, the two following assumptions are made. The rotary valve (RV-1) is a volumetric feeder so it is assumed that the volumetric feed rate through RV-1 is the same for any given shaft speed as to the operating conditions under which RV-1 was calibrated via observation this was seen to be generally true. It was also assumed that the adsorbate on the spent carbon is 10% fixed carbon and 90% volatile matter as determined via numerous grab analyses for volatile matter.

Carbon Loss

The carbon loss can then be calculated as follows:

$$\text{Carbon Loss, weight percent} = \frac{ER_1 + ER_2}{R_W} (100)$$

$$= \frac{\left[ER_1 + 0.251 \dfrac{W_{H_2O}}{At} \dfrac{W_{T} - W_{FP}}{V_{FIL}} \right] 100}{R_V \; (AD) \left[\dfrac{100 - (P_{VOL}/0.9)}{100} \right]}$$

Mass Balance Procedure #2 (By MWW)

Introduction

This analysis evaluated fine production in all the individual waste streams and required filtration and quantification of suspended solids taken from the waste streams. It is also required quantification of waste stream flow rates.

The points of waste stream sampling as shown in Figure A-1, 2 were the following:

1. ST-1 Overflow
2. DS-1 Overflow
3. QT-1 Overflow
5. ST-2 Overflow
7. Common Effluent Drain

Procedure

A filtration procedure was utilized with a vacuum flask at 10 psig vacuum with Millipore FHLP 090-25 (.5 um) filters and type AP515 090 00 prefilters. Five hundred ml samples were filtered unless otherwise noted using standard industry procedures for drying and weighing. Three replicates were performed to determine final value. Flow rates were determined using grab samples due to the installation requirements. Overall fine loss was calculated from the common effluent stream solely as this was the collection point for all losses incurred through abrasion and fining in the FBR system (Figure A-1).

Discussion

This analysis did not take into account: 1) gassified base carbon and 2) fines occurring in ST-2 which do not go to overflow, but become entrained in the tank. These carbon fines are later backwashed out of the contractor.

Although stack gas particulate emissions were not measured for each analysis, values were assumed from previous measurements to be consistent.

Mass balance was not used to calculate overall stream loss as there was no way readily apparent to qualify transport losses.

General Volumetric Loss Procedure #1 (By Westvaco)

Process Flow and Discussion

The process flowsheet for the carbon reactivation system is presented in Figures A-1, A-2. The volume method involves determination of the change in carbon volume after reactivation. To determine the initial carbon volume in the spent carbon storage tank (ST-1) the height of carbon in the tank was measured at a number of points to define the shape of the carbon surface. The height measurements were made along specific radii of the tank, then a symmetrical shape of the surface was assumed or average heights used to project a shape. Using these height measurements and the dimensions of ST-1, the initial carbon volume was calculated. This carbon volume was at a given carbon bulk density. If there was any carbon in the reactivated carbon storage tank (ST-2), the initial carbon volume must also be dewatered using the same procedure.

The carbon reactivation system was then operated with no carbon transfer to or from the carbon filters. At the end of that time, the final carbon volume was determined for ST-1 and ST-2 by the same procedure discussed above.

Carbon Volume Determinations

Referring to Figure A-3, the carbon in each carbon storage tank is depicted with the carbon height measurements along a particular radii. For the planned certification run at Manchester, the recommendations were to conduct the volumetric

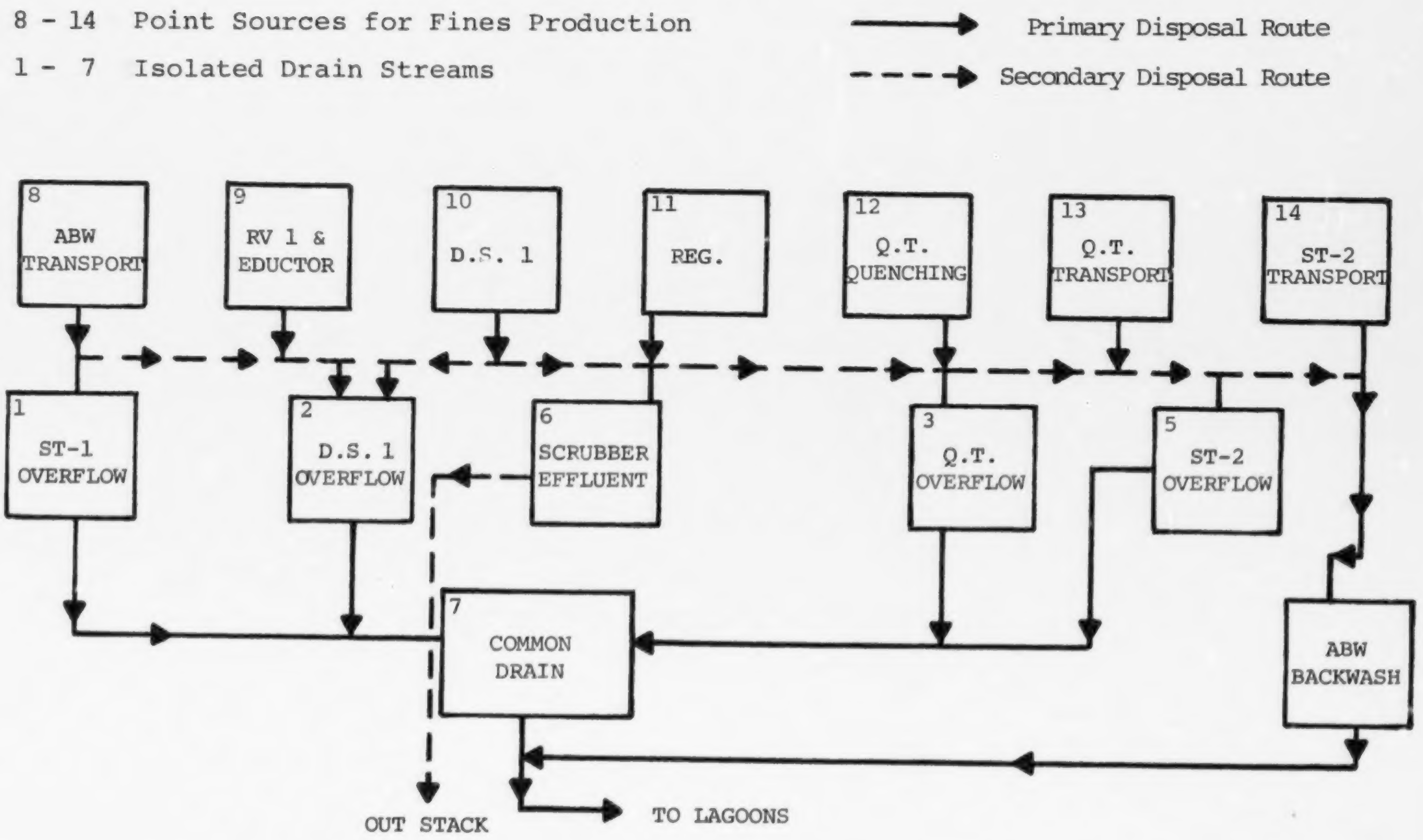
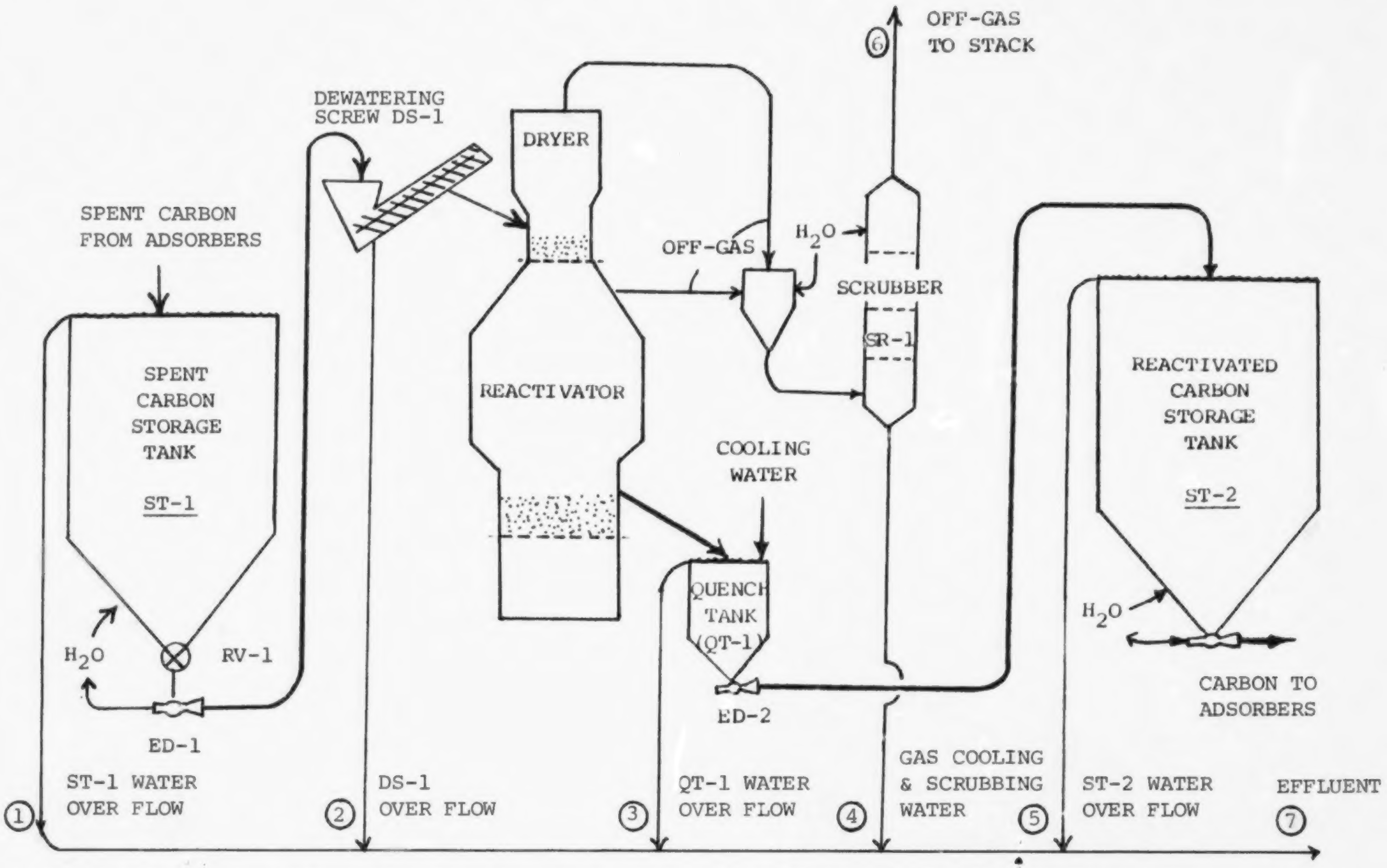

8 - 14 Point Sources for Fines Production
1 - 7 Isolated Drain Streams
Primary Disposal Route
Secondary Disposal Route
8 ABW TRANSPORT
9 RV 1 & EDUCTOR
10 D.S. 1
11 REG.
12 Q.T. QUENCHING
13 Q.T. TRANSPORT
14 ST-2 TRANSPORT
1 ST-1 OVERFLOW
2 D.S. 1 OVERFLOW
6 SCRUBBER EFFLUENT
3 Q.T. OVERFLOW
5 ST-2 OVERFLOW
7 COMMON DRAIN
ABW BACKWASH
OUT STACK
TO LAGOONS

Figure A-1. Diagramatic representation of fines production and disposal through fluid-bed system in Manchester, NH



OFF-GAS TO STACK
⑥
DEWATERING SCREW DS-1
DRYER
SPENT CARBON FROM ADSORBERS
OFF-GAS
H_2O
SCRUBBER
SR-1
SPENT CARBON STORAGE TANK
ST-1
REACTIVATOR
REACTIVATED CARBON STORAGE TANK
ST-2
COOLING WATER
QUENCH TANK (QT-1)
H_2O
RV-1
H_2O
ED-1
ED-2
CARBON TO ADSORBERS
GAS COOLING & SCRUBBING WATER
ST-1 WATER OVER FLOW
DS-1 OVER FLOW
QT-1 WATER OVER FLOW
ST-2 WATER OVER FLOW
EFFLUENT
①
②
③
④
⑤
⑦

Figure A-2. Process flowsheet for sources of carbon loss fluid-bed reactivation system.

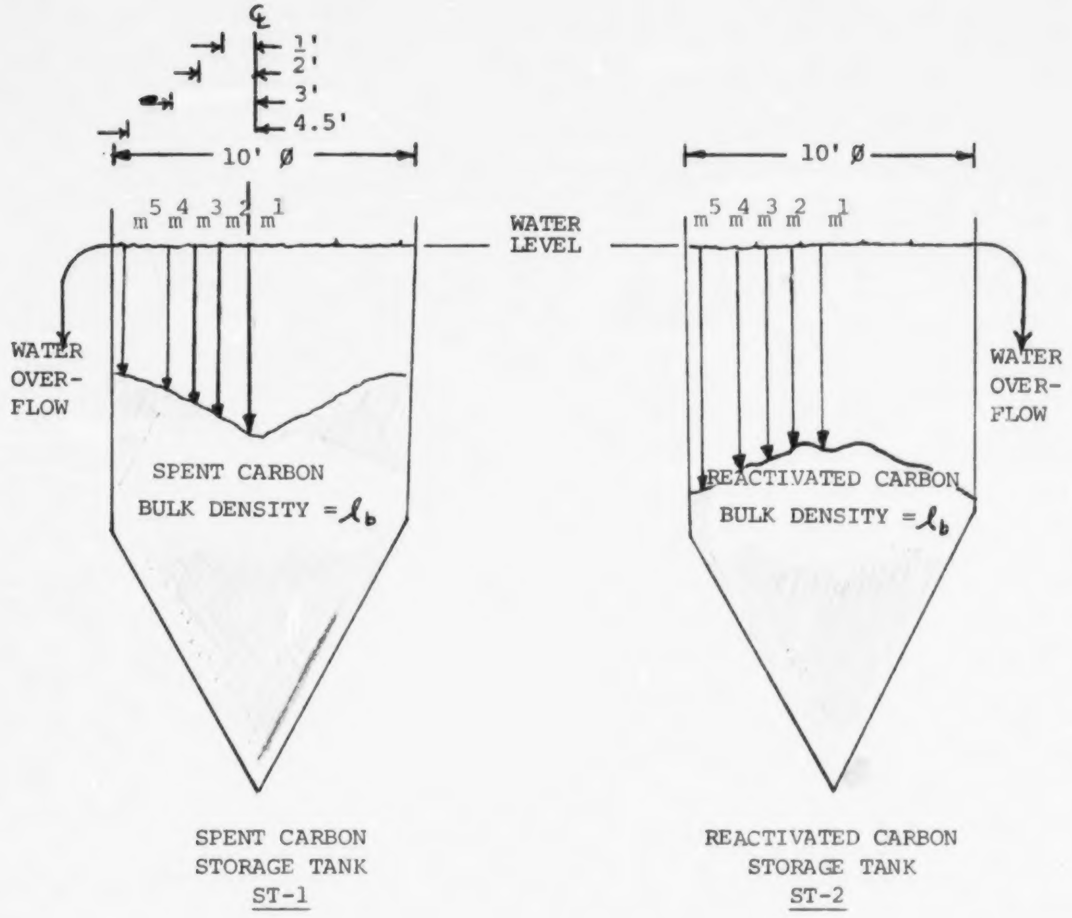

℄
1'
2'
3'
4.5'
10' Ø
m^5 m^4 m^3 m^2 m^1
WATER LEVEL
WATER OVER-FLOW
SPENT CARBON
BULK DENSITY = ρ_b
SPENT CARBON STORAGE TANK ST-1
10' Ø
m^5 m^4 m^3 m^2 m^1
WATER OVER-FLOW
REACTIVATED CARBON
BULK DENSITY = ρ_b
REACTIVATED CARBON STORAGE TANK ST-2

Figure A-3. Carbon height measurement in carbon storage tanks.

carbon loss procedure as follows:

1. With the carbon reactivation system operating at steady state, time zero for the start of the run was with ST-2 empty and with ST-1 half to completely full.

2. Carbon heights from the water interface M_1 through M_5 (in fett) along 4 radii in ST-1 were measured. Each of the M's corresponding to a certain distance from the center of the tank were averaged, then the surface at that circumference was assumed uniform at that average height (the individual measurements along a radii will be discussed later for an uncertainty analysis.)

   GAC volume loss percent = (GAC volume ST-1 - initial GAC volume ST-2 final)/(GAC volume ST-1 initial) x 100

3. The desire to start the run with ST-2 empty but, if this is not possible, then the initial volume would have to be determined for ST-2 and would be given as:

   Relative initial carbon volume in ST-2, $M^3 = {}^{V}\text{ST-2}$

4. The reactivation system was run until ST-2 was empty. Operate cone agitation at least one hour as had been done in ST-1 during steady state. If the 2 tanks were operated identically prior to measurement of carbon volume, then the carbon density in each tank (on an adsorbate-free basis) can be considered equal. Next, measure the carbon volume in ST-2 as in step 2 for ST-1. The carbon volume in ST-2 is then calculated.

5. The desire is to run until ST-1 is empty but, if this is not possible, then the final volume in ST-1 would be required to complete loss.

Carbon Loss Determination

From the volume measurements above, the volumetric carbon loss equation is:

$$\text{Volumetric carbon loss, volume percent} = \frac{(\text{ST-1}) - (\text{ST-2})}{(\text{ST-1})}$$

$$\times\ 100$$

Further, if the carbon storage tanks are operated as desired $(V_{ST-1})f = (V_{ST-2})i = 0$, and the carbon loss equation is simplified as:

$$\text{Volumetric carbon loss, volume percent} = \frac{\text{ST-1} - \text{ST-2}}{\text{ST-1}} \times 100$$

Certification Run Analysis for Volumetric Loss Procedure #2 (By MWW)

Process Flow and Discussion

The process flowsheet for the carbon reactivation system is given in Figure A-2. The volume balance method involved determination of the change in carbon volume after reactivation. To determine the initial carbon volume in the spent carbon storage tank (ST-1), the height of the carbon in the tank was measured at a number of points to define the shape of the carbon surface. The height measurements were made along specific radii of the tank, then a symmetrical shape of the surface was assumed or average heights used to project a shape. Using these height measurements and the dimensions of ST-1, the initial carbon volume was calculated. If there is any carbon in the reactivated carbon storage tank ST-2, the initial carbon volume must also be determined by the same procedure.

The carbon reactivation system was then operated with no carbon transfer to or from the carbon adsorption system. At the end of that time, the final carbon volume was determined for ST-1 and ST-2 by the same procedure discussed above. Any differences in carbon bulk density would have to be taken into account. The volumetric carbon loss can then be calculated.

Carbon Volume Determinations

Referring to Figure A-3, the GAC volume in each carbon storage tank was determined with the carbon height measurements along 4 perpendicular radii. For the planned certification run at Manchester, the recommendation was to conduct the volumetric carbon loss procedure as follows.

1. With the carbon reactivation system operating at steady state, time zero for the start of the run was with ST-2 empty and with ST-1 completely full.

2. Measure the carbon heights from the water interface M_1 through M_5 (in feet) along 4 radii in ST-1. This produced 21 separate measurements.

Fluid-Bed System Volumetric Loss Procedure #3 (By MWW)

Fluid-Bed Loss Determination

The determination of losses was made by both volumetric and mass balance procedure as described below. The determination was made over an approximately 55-hour period and entailed the reactivation of the entire concents of ST-1 which was full upon starting the evaluation.

Volumetric Procedure

Volumetric reactivation losses were accounted for using the basic procedures established by Westvaco. Exceptions are specified below and specific modifications to this procedure were the following:

1. Neglect bulk density considerations. To compensate for this simplification, throat water agitators were operated on both tanks throughout the reactivation cycle. This equivalent set of conditions should compensate for the bulk density variances encountered between ST-1 and ST-2 through unequal fill rates and different levels of tank vibration encountered in the different parts of the reactivator room.

2. Two measuring techniques were used to establish the carbon-water interface in an attempt to minimize error. The most repetitive of the measurement techniques involved the use of a stadia rod with a platform base.

   A. The first measurement set was the settled carbon interface before agitation. Four sets of radius measurements were made. Increased number of radius measurements statistically reduced the error due to measurement technique by increasing the replicates on each point.

   B. The carbon interface was raked smooth with a hand rake. Upon obtaining a level surface, the carbon interface measurements were repeated as described above.

   C. The above 2 measurements in ST-2 were repeated upon completion of the reactivation of ST-1 (empty tank). Only 2 measurements of carbon volume were needed before and after reactivation.

As an alternative to Westvaco's calculational procedure (a 5 point volume measurement), a method using the best-fit line may be substituted. In this procedure, the 4 sets of radius measurements are averaged to find the best fit line through them. The central point and wall intercept are then determined. This provides the necessary information to construct a right circular cone whose volume can be manipulated to determine the overall volumes concerned.

Filter to Filter Volumetric Loss Procedure #4 (By MWW)

General

This procedure applies to a volumetric test for the determination of total GAC losses stemming from (thermal) reactivation, fluid transport, and backwashing at MWW. Monitoring for these losses was accomplished at the Manchester WTP, test filter #1, beginning with the second reactivation test period in June 1980. This procedure was followed in all subsequent reactivations of the test filter.

Frequency

The volume of GAC in the test filter was assessed at the start of the adsorption cycle immediately after reactivation and at the end of the adsorption cycle.

Procedure

The carbon filter volume was measured as described below:

1. Carbon filter #1 was thoroughly backwashed.
2. The influent channel slide gate was inserted to eliminate flow through the filter.
3. At least one hour then elapsed to allow for the filter head to dissipate. As a check to ascertain equalized filter head, graduations in one-half inch increments were affixed to the filter wall.
4. Using the stadia rod device, carbon interface height measurements were made on each filter cell at a distance of 2, 5, 8, 11 and 14 feet from the filter wall. These measurements were made from the carbon surface to the water level.
5. All measurements were then recorded and averaged for each media.
6. Carbon volume changes were determined as follows:
    A. All measurements taken on media was averaged to determine (1_A), the average water depth above the carbon surface.
    B. The depth of the filter water from the top of the cell plate to water surface (W_D) was then subtracted from the above measurement to obtain the average interface height (C_L) below the top of the filter structure:

       $$C_L = 1_A - W_D$$

    C. C_L (M) was then subtracted from 1.2 to give the

6. C. Continued

actual average carbon depth ($1.2 - C_L = C_A(M)$) in the respective filter half.

D. The value of C_A (M) was then multiplied by the horizontal surface area of each filter half to provide an in-place measurement of actual carbon volume in M^3 (V_T):

$$V_T = 1.23\ M\ (1_A - W_D) \times 4.9 \times 16.9$$

7. The percentage change of carbon volume was then calculated as follows:

$$\text{Percent loss at } 90\pm \text{ days} = \frac{V_{T_O} - V_{T_{90}}}{V_{T_O}} \times 100$$

Point of Source Volumetric Loss Procedure #5 (By MWW)

Intent

This loss procedure is intended to individualize the sources of carbon loss in a filter to filter (contactor to contactor) reactivation sequence. It is broken down into 5 individual loss procedures which are listed below. It is important that a homogeneous source of GAC be utilized on which to perform these comparative analyses.

The individual procedures #1, #2, and #3 were accomplished through bypassing various phases of the reactivation system. As detailed in each procedure, only the components specifically mentioned were involved in production of carbon losses. It is apparent that simulating conditions to isolate these various system components required some amount of bypassing and rerouting of GAC streams through the reactivation system.

Procedure

1. The first analysis is intended to show only those losses incurred through transport outside the reactivation system (battery limits). As such, the following procedure is followed:

   A. Twelve cells of homogeneous GAC are backwashed, drained and measured at 72 points for their volume (6 points/cell).

   B. The GAC is then educted completely with a 3-inch Amtek eductor at 60 psig to ST-2.

1. C. ST-2 is then emptied again with a 3-inch eductor to the contactor.

   D. The cells are then thoroughly backwashed, drained and measured as in 1. A. above.

   E. Volume loss is then computed as $\frac{Va - Vd}{Va} \times 100$

2. This analysis is intended to demonstrate those losses incurred in item 1 above plus FBR systems RV-1 and Ed-1.

   A. Twelve cells of homogeneous GAC material in the same state as item 1 above is backwashed and measured as described in item 1. A. above.

   B. This material is measured and transported as in item 1. B. above to ST-1.

   C. The GAC is then transported from ST-1 to ST-2, utilizing RV-1 and Ed-1.

   D. The GAC is then moved back to the contactor as in item 1. C. above and measured as in item 1. D. above.

   E. Volume loss is then calculated as in item 1. E. above.

3. This analysis is designed to bring out the losses of item 2. plus the losses incurred by DS-1 and E-2. These are all the losses excluding reactivation itself.

   A. All measurements and transportations are handled as in item 2 above except for the following

      1) In going from ST-1 to ST-2, the GAC follows the typical FBR system until it reaches the dryer. There, it is intercepted and diverted through a 3-inch hose to QT-1. Water is sent through the hose with the GAC to prevent clogging.

   B. Final transport and measurement are handled as in item 1. C., 1. D. and 1. E. above.

4. This analysis demonstrates full system (contactor to contactor) losses. As part of this analysis, we also performed an analysis on volume loss from ST-1 to ST-2 through the procedure outlined in item 5. below.

   A. The system to system losses are determined via a

4. A. before and after measurement procedure as in item 1.A., 1.B., 1.C., 1.D., and 1.E.

   B. ST-1 to ST-2 losses are determined via the following procedure.

Fluid-Bed Volume Loss Procedure (ST-1 to ST-2)

1. Any bulk density differences in the 2 tanks (ST-1 and ST-2) caused by unequal fill rates and different levels of tank vibration are to be compensated for by operating the throat water agitators on both tanks throughout the reactivation cycle.

2. With the GAC in its untouched semi-conical form at the GAC/water interface, 4 sets of radius measurements are to be made on this interface for each tank. Using a modified stadia rod, measurements are to be made in one-foot increments from the center of each tank to the wall (total of 21 rod measurements per tank). These measurements will be directly from the water level of each tank, thereby eliminating corrections because of angle iron sag.

3. From the above measurements, calculate the volume of carbon in each tank by the following method:

   A. Average the 4 rod readings (s) at each distance from the center line, or radius (r), to determine an "average cross section".

   B. Starting at r = 5.0 (the tank wall) find the differences in radius and in average rod reading between adjacent measurements, ALWAYS subtracting the measurement made closer to the center line from the more distant measurement. (Resulting differences in radius will be positive; differences in rod reading will be positive or negative, corresponding to whether the component value will be added to or subtracted from the tank volume.)

   C. Find the altitudes (h) of the large and small cones corresponding to each component volume by multiplying the slope (ratio of difference in rod reading to difference in radius) by the radii of the measurements defining that component. ("Large corresponds to the larger value of radius, and indicates a larger absolute magnitude, though algebracially a negative value may be less than that of the "small" cone altitude.)

   D. Find the resulting relative volumes ($V = r^2h$) of the large and small cones corresponding to each

3. D. Continued

component volume. (These volumes may be positive or negative as determined by the difference in rod reading previously calculated.)

ALTERNATIVE TO STEPS 3 and 4: Calculate each relative volume in one step by multiplying the slope by the radius cubed ($V = \text{slope} \times r^3$), using the appropriate slope and radii for the large and small cones corresponding to each component volume.

E. Find the sum of the large-cone relative volumes.

F. Subtract from this sum, the sum of the small-cone relative volumes.

G. Multiply this difference by $\pi/3$ to obtain the total positive or negative volume.

H. Compute the cylindrical volume of the tank from the base to the average surface level at the tank wall ($S_{5.0}$), that is:

$$\pi\,(5.0\text{ ft})^2\,(11.58\text{ ft} - S_{5.0})$$

I. Compute the conical volume of the base of the tank, that is:

$$(\pi/3)\,(5.0\text{ ft})^2\,(8.05\text{ ft})$$

J. Add the volumes found in 7, 8 and 9 to obtain the total volume in the tank. (The positive or negative sign on the cone-like volume constructed from the surface measurements will properly indicate its addition to or subtraction from the tank volume.)

4. Calculate volume loss:

$$\frac{V_{ST-1} - V_{ST-2}}{V_{ST-1}} \times 100 = \text{Percent Loss}$$

EPA Suggested Tank Volume Calculational Procedure

The following procedure concerns the problem with determination of the volume of GAC in storage tanks (before and after reactivation), given the dimensions of the tanks and rod measurements of the carbon surface. The sample data examined is summarized in the first 2 attachments: the rod readings (distance, in feet, below the top of the tank) were taken at the radii indicated, along perpendicular diameters. These are listed and plotted in the first attachment, giving an idea of the shape of the surface. The second attachment shows the dimensions of the tanks and the crux of the problem: to transform the rod measurements into an accurate estimation of the cone-line volume to be added to or subtracted from the volume of the tank if filled level.

The 2 methods proposed by the MWW may be summarized as follows:

METHOD 1: Average the readings at each radius; then use linear regression to determine a "best-fit" line, with intercepts at the wall and center line of tank to express the elevation versus radius data. Revolution of this line, using the center line as an axis, determines a cone, the volume of which ($\pi r^2 h/3$) may be added or subtracted from the tank volume (a conical volume at the base plus a cylindrical volume from the base to the wall intercept).

METHOD 2: Average all 17 readings to determine the average level of the carbon surface, and compute the volume as the conical volume at the base plus a cylindrical volume up to this average level.

An approach taken more directly from the rod readings would be construction of the cone-like volume (to be added or subtracted) using a stack of frustums or conical sections, each defined by a line segment between 2 adjacent readings (on the same diameter). Each component of the volume is found by extrapolating the corresponding line segment to intersect the center line, defining by similar triangles the altitudes of the larger cone (which includes the frustum) and the smaller cone (which excludes the frustum), and taking the difference between the volumes of these 2 cones. Each radial cross-section could determine a volume assembled from such components, and a total volume, formed by the sum of one quarter of each of the 4 determined volumes, would probably be the best linear representation of the volume to be added or subtracted that can be justified on the basis of the measurements.

A "Method 3" for making volume calculations, based on the preceding paragraph, is described below. Note that summine one quarter of the volume determined by each cross section (as mentioned above) is actually an averaging of the 4 determined volumes; an alternative (and equivalent) technique, used below, is to average the rod readings taken at each distance from the center of the tank and determine one total volume directly. Note also that a measurement at the tank wall must be made or assumed.

METHOD 3:

1. Average the 4 rod readings (s) at each distance from the center line, or radius (r), to determine an "average cross section".

2. Starting at r = 5.0 (the tank wall) find the differences in radius and in average rod reading between adjacent measurements, ALWAYS subtracting the measurement made closer to the center line from the more distant measurement. (Resulting differences in radius will be positive; differences in rod reading will postive or negative, corresponding to whether the component volume will be added to or subtracted from the tank volume.)

3. Find the altitudes (h) of the large and small cones corresponding to each component volume by multiplying the slope (ratio of difference in rod reading to difference in radius) by the radii of the measurements defining that component. ("Large corresponds to the larger value of radius, and indicates a larger absolute magnitude, though algebraically a negative value may be less than that of the "small" cone altitude).

4. Find the resulting relative volumes ($V = r^2h$) of the large and small cones corresponding to each component volume. (These volumes may be positive or negative, as determined by the difference in rod reading previously calculated.)

ALTERNATIVE TO STEPS 3 AND 4: Calculate each relative volume in one step by multiplying the slope by the radius cubed ($V = \text{slope} \times r^3$) using the appropriate slope and radii for the large and small cones corresponding to each component volume.

5. Find the sum of the large-cone relative volumes.

6. Subtract from this sum the sum of the small-cone relative volumes.

7. Multiply this difference by $\pi/3$ to obtain the total positive or negative volume.

8. Compute the cylindrical volume of the tank from the base to the average surface level at the tank wall ($S_{5.0}$), that is,

$$\pi\ (5.0\ \text{ft})^2\ \ (11.58\ \text{ft} - S_{5.0})$$

9. Compute the conical volume of the base of the tank, that is,

$$(\pi/3)\ (5.0\ \text{ft})^2\ \ (8.05\ \text{ft})$$

10. Add the volumes found in 7, 8 and 9 to obtain the total volume in the tank. (The positive or negative sign on the cone-like volume constructed from the surface measurements will properly indicate its addition to or subtraction from the tank volume.)

Though Method 3 appears to be rather involved, it is geometrically sound, fitted to the measurements taken, and requires only algebraic manipulations. It is easily organized into tabular form, and should be easy to program into a small computer or programmable calculator.

The results from Method 3 applied to the sample data for ST-1 and ST-2 are very close to those of Method 1, seeming to validate it, and differ greatly from the results obtained by applying Method 2 as indicated below:

Volume Estimations

Method	ST-1	ST-2
1	922.06	841.42
2(A)	903.47	867.21
2(B)		972.79
3	921.73	842.80

First, note that, while averaging a whole set of measurements for a rectangular area sampled in a regular grid would be valid, a circular area is another story. In particular, would the method work if the surface was truly conical? In such a case, if we adapt Method 2 to take sets of 4 measurements spaced at regular increments of radius from the center of the tank wall, the average would yield a cylindrical volume with one-half the altitude of the cone. This volume would, of course, have one-half the volume of a cylinder with the same altitude of a cylinder with the same altitude. In this case, Method 2 would underestimate the volume in ST-1 and overestimate the volume in ST-2.

Looking at it another way, note that if a series of concentric circles is constructed at regular increments of radius, the area between 2 adjacent circles increases with the radius; the spacing between circles remains the same, but the circumferences increase linearly (C-2IIr). Because the volume is calculated as a function of the area multiplied by the altitude, if an equal number of rod readings are taken at each radius (as in the present measurement procedure), those further from the center of the tank represent not only more of the plan area, but a greater portion of the volume. This of course depends on the actual rod readings involved, but to average a set of measurements at different radii and use this average to accurately define the top elevation of a cylindrical volume, a scheme must be devised to "weight" the measurements in relation to their number and relative distances from the center of the tank. Rod readings taken at the same radius, however, would be "weighted" equally, as done in Methods 1 and 3.

The apparent error in Method 2 is that a "weighting" is not used. In a sense, an arbitrary "weighting" is made becuase only one measurement is made at the center, but this is more than offset (in the wrong direction) by having only one set of measurements beyond 3 feet from the center of the tank; "weighting" was probably not considered in suggesting this method, however. The volume being calculated is certainly not conical, either; but if the results of Methods 1 and 3 are reasonably accurate calculations of the volumes in ST-1 and ST-2 then the results of Method 2 are under-and overestimates, respectively, of these volumes, as was expected.

Based on the above discussion, Method 3 should be implemented in some form for calculation of volumes of GAC in storage tanks like ST-1 and ST-2. Method 2 should NOT BE USED UNLESS a "weighting" scheme is matched to the measurement locations in the tank. Method 1 has given comparable results to Method 3 in the 2 cases examined, but if the surface is less regular, fitting a straight line to the points may not be quite as accurate. Method 3 is geometrically based directly upon the measurements taken, and uses basic algebra rather than linear regression; thus, it should be easy to apply and as accurate as the present method of measurement will justify.

Additionally, measurements should be taken at regular intervals from the center of the tank all the way to the tank wall, perhaps at one-foot increments (which would be 21 rod readings). It would be more accurate to provide relatively more measurements in the regions of great change in slope, but the locations of these regions in the tank are not really known, and are different in ST-1 and ST-2. Regular spacings (such as one foot) will make measurements, and even calculations a bit easier to perform.

APPENDIX B

MONITORING PROGRAM SUPPLEMENTAL GRAPHICS

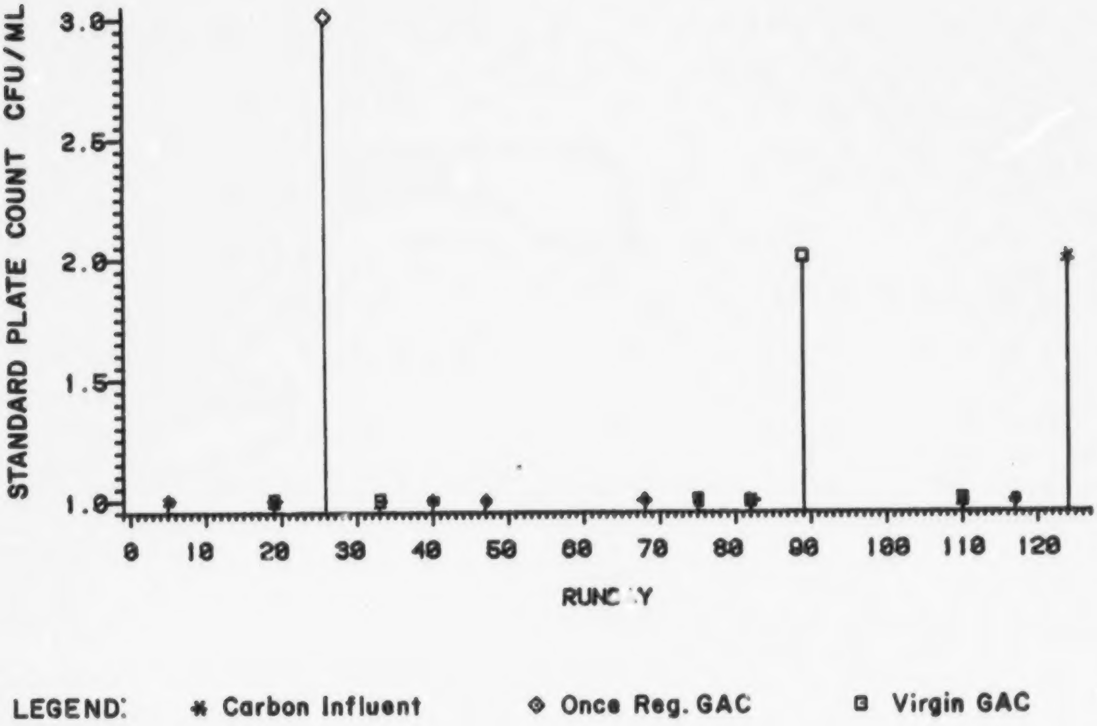


Figure B-1. Run 1.-Test filter standard plate count.

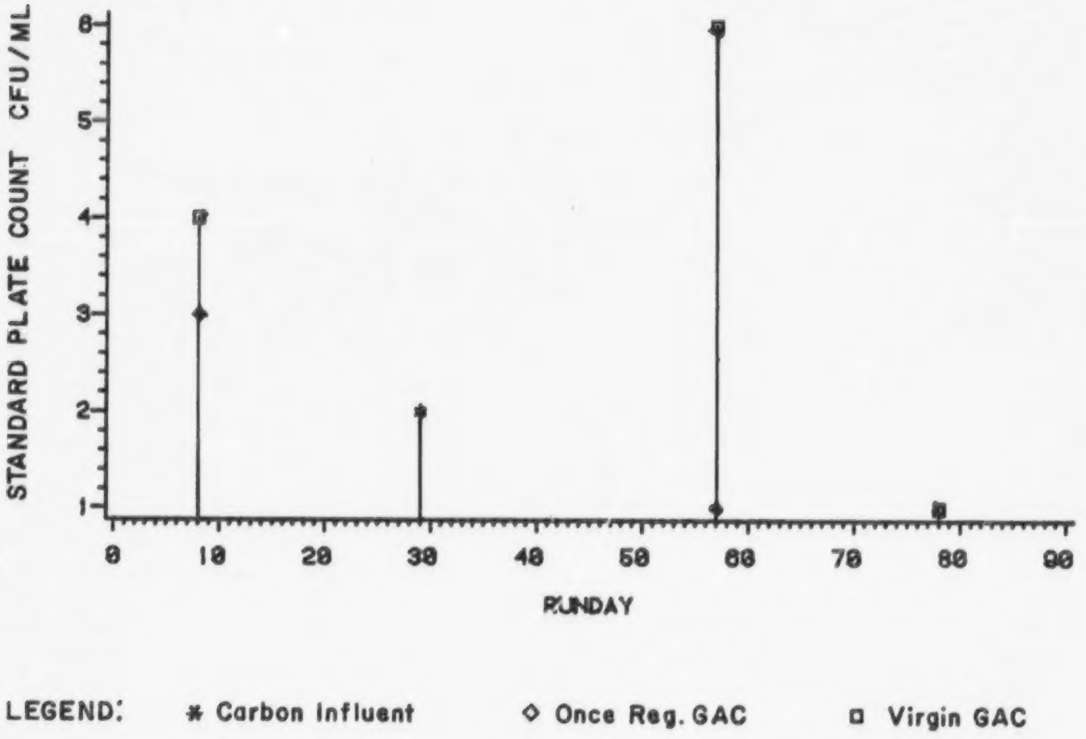


Figure B-2. Run 3.—Test filter standard plate count.

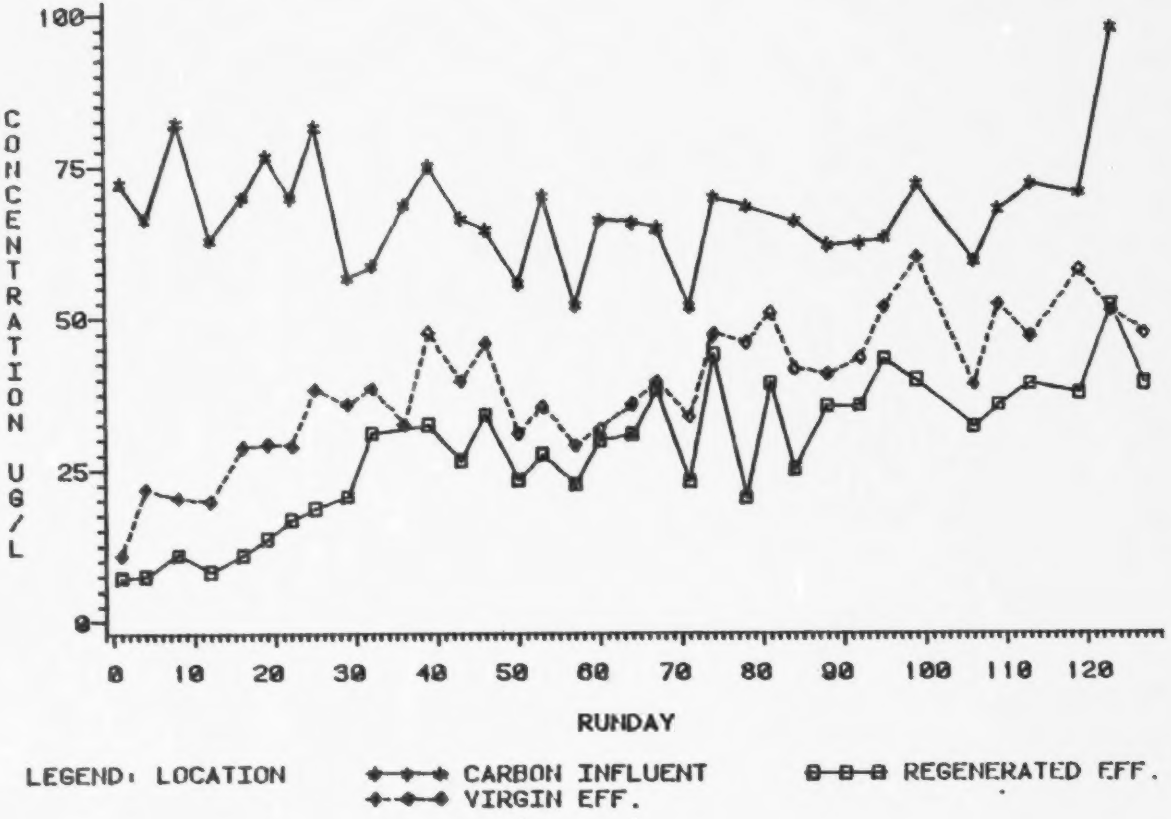


Figure B-3. Run I.–Three day ambient THMFP breakthrough curves.

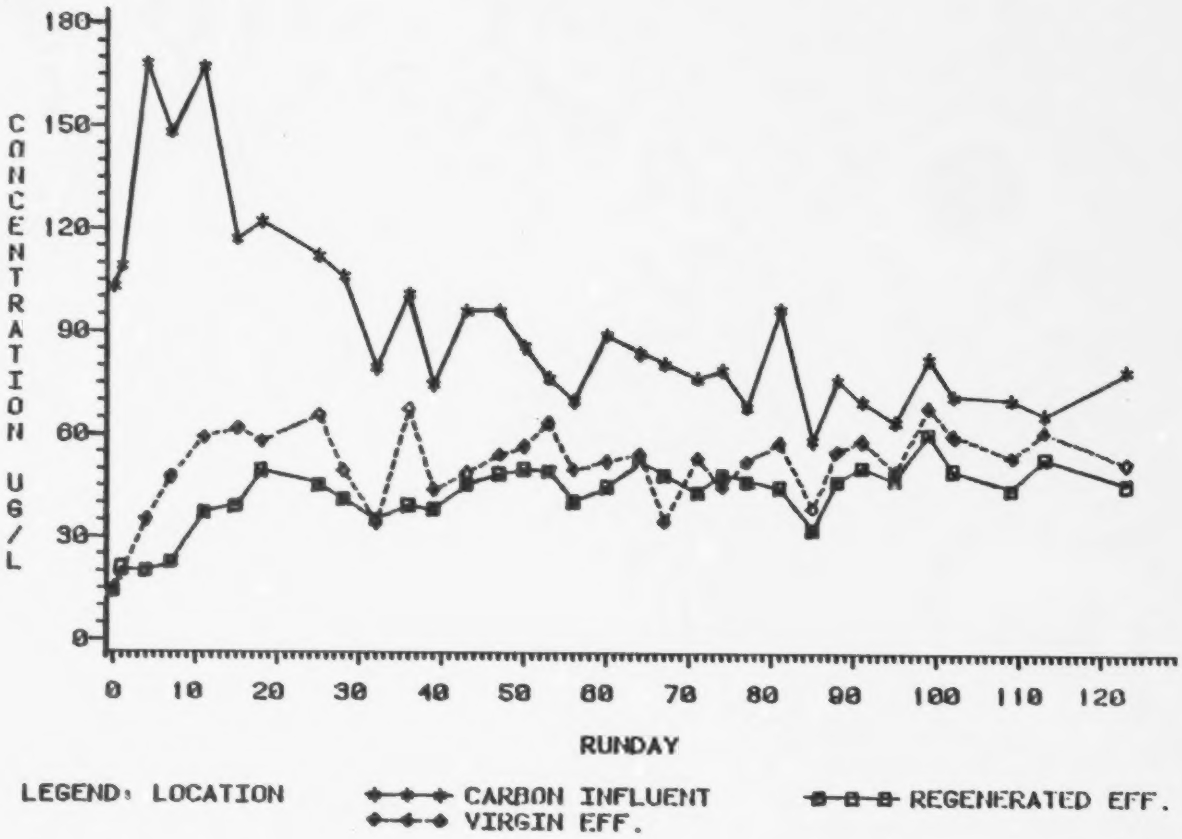


Figure B-4. Run 2.- Three day ambient THMFP breakthrough curves.

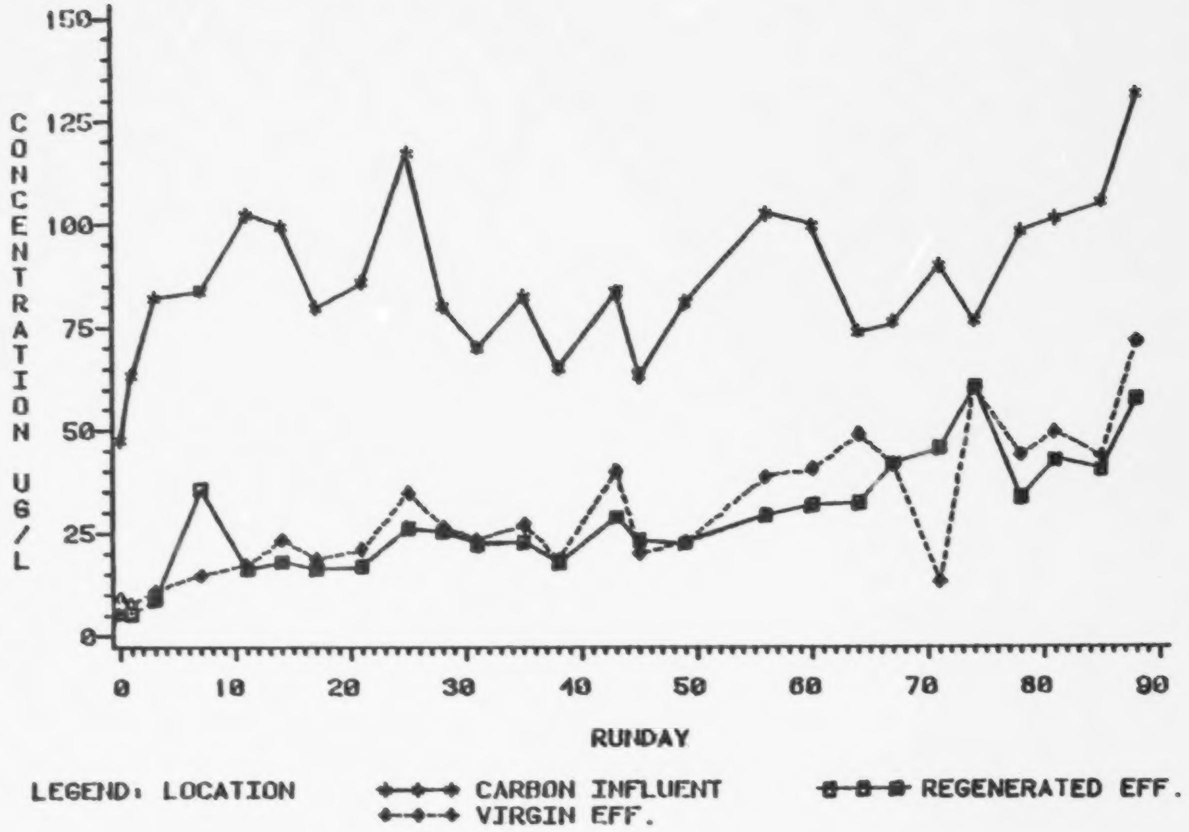


Figure B-5. Run 3.-Three day ambient THMFP breakthrough curves.

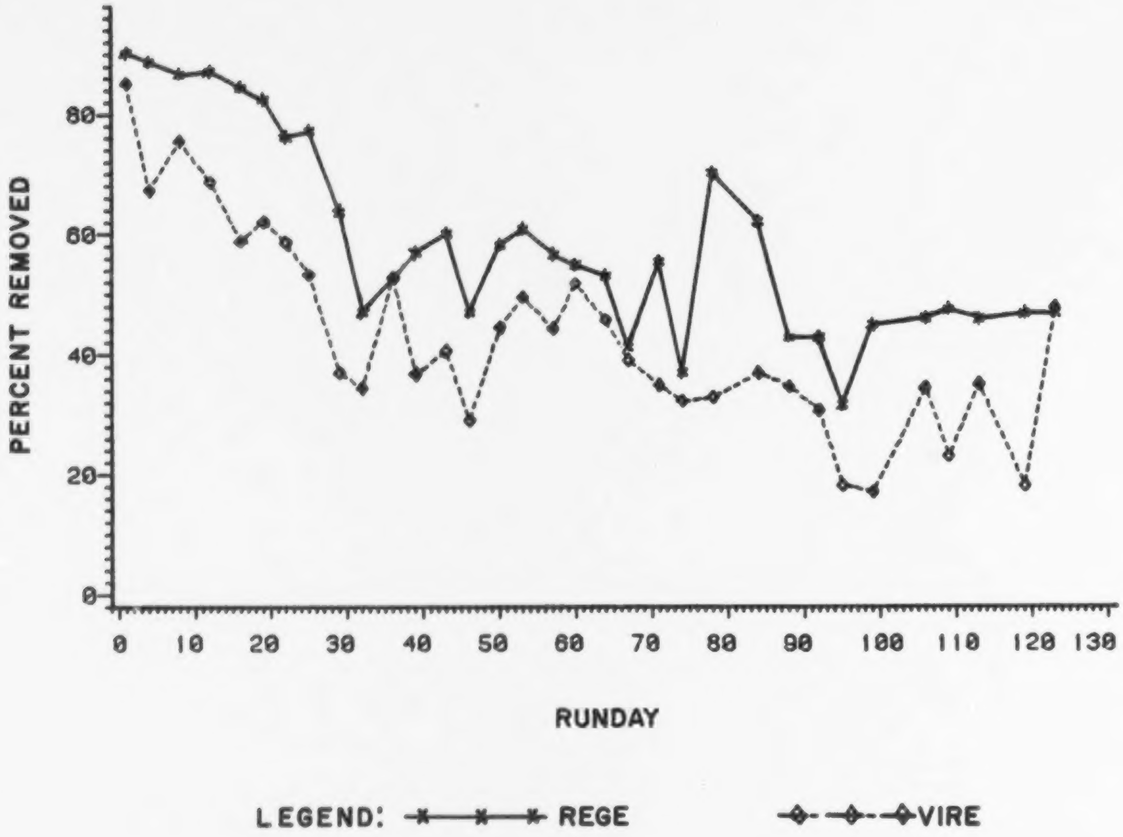


Figure B-6. Run I.- Percent removal 3 day amb. THMFP curves.

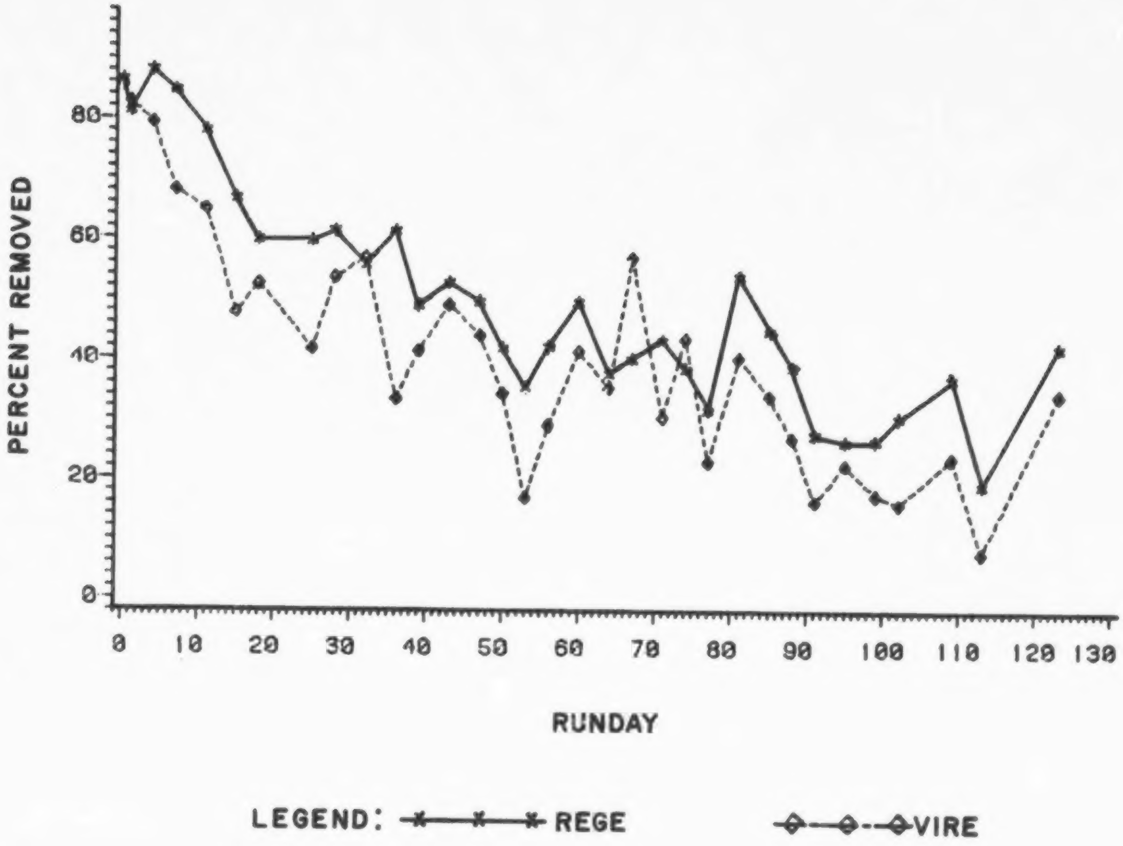


Figure B-7. Run 2.—Percent removal 3 day amb. THMFP curves.

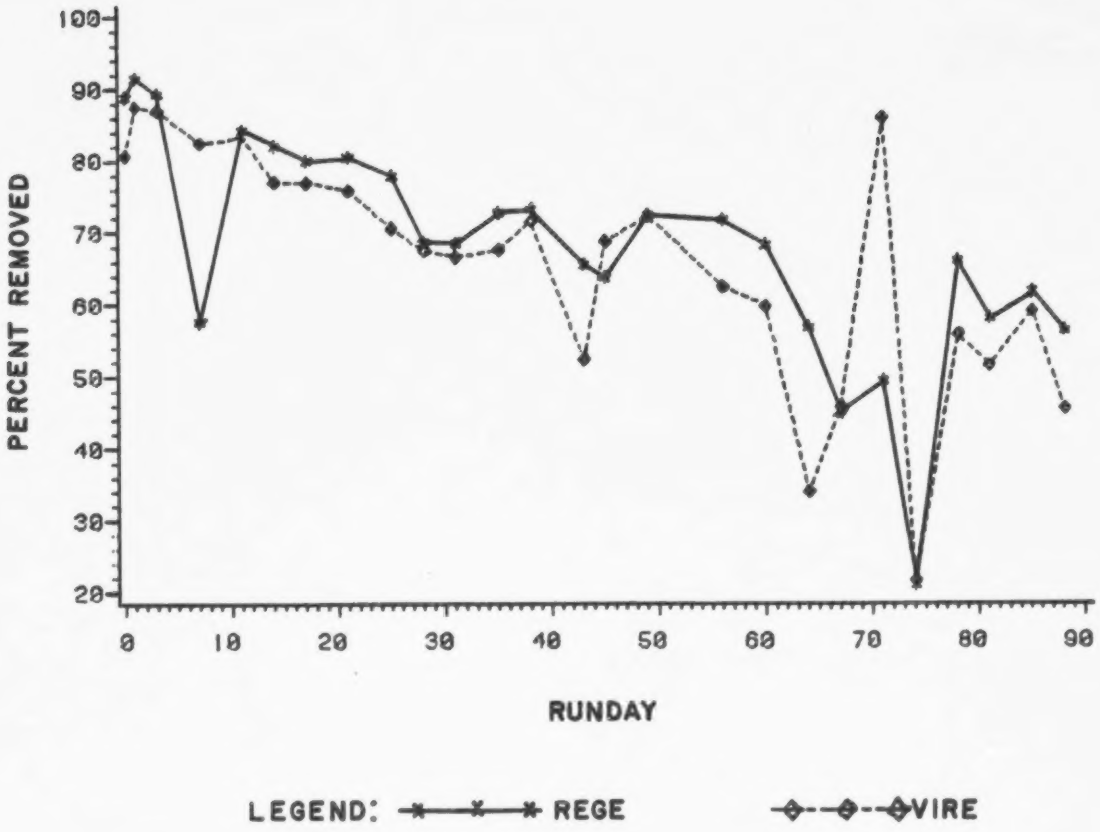


Figure B-8. Run 3.— Percent removal 3 day amb. THMFP curves.

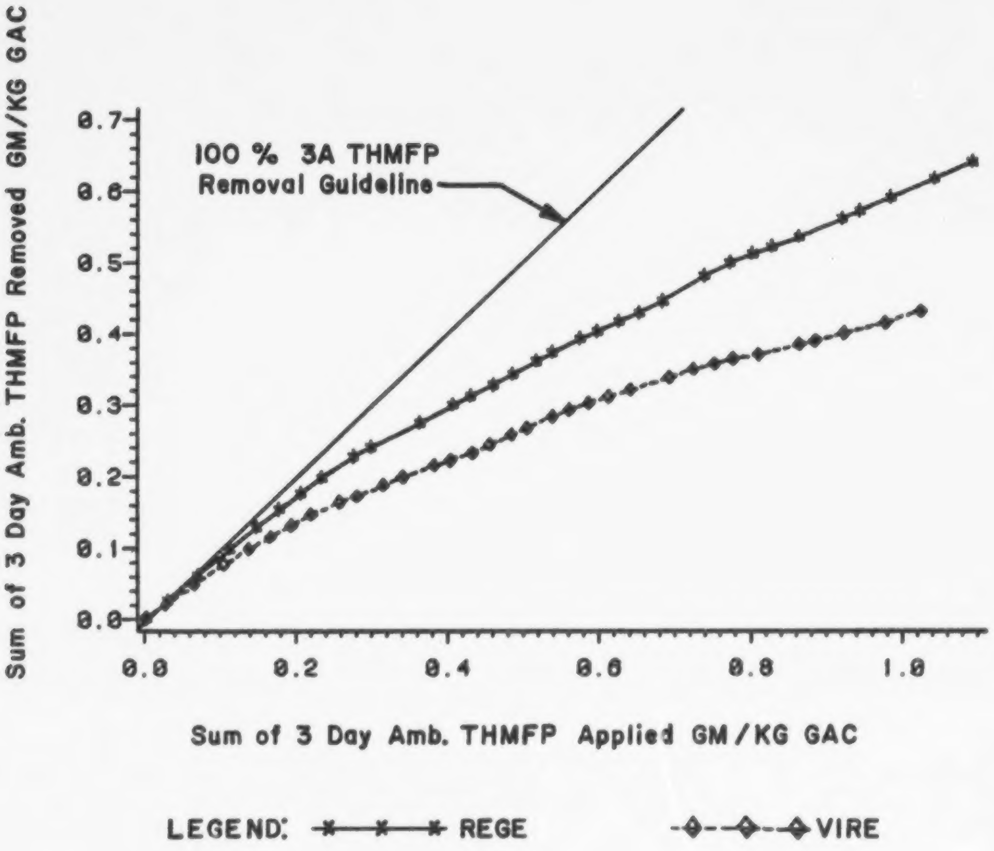


Figure B-9. Run I.—3 day amb. THMFP loading curves.

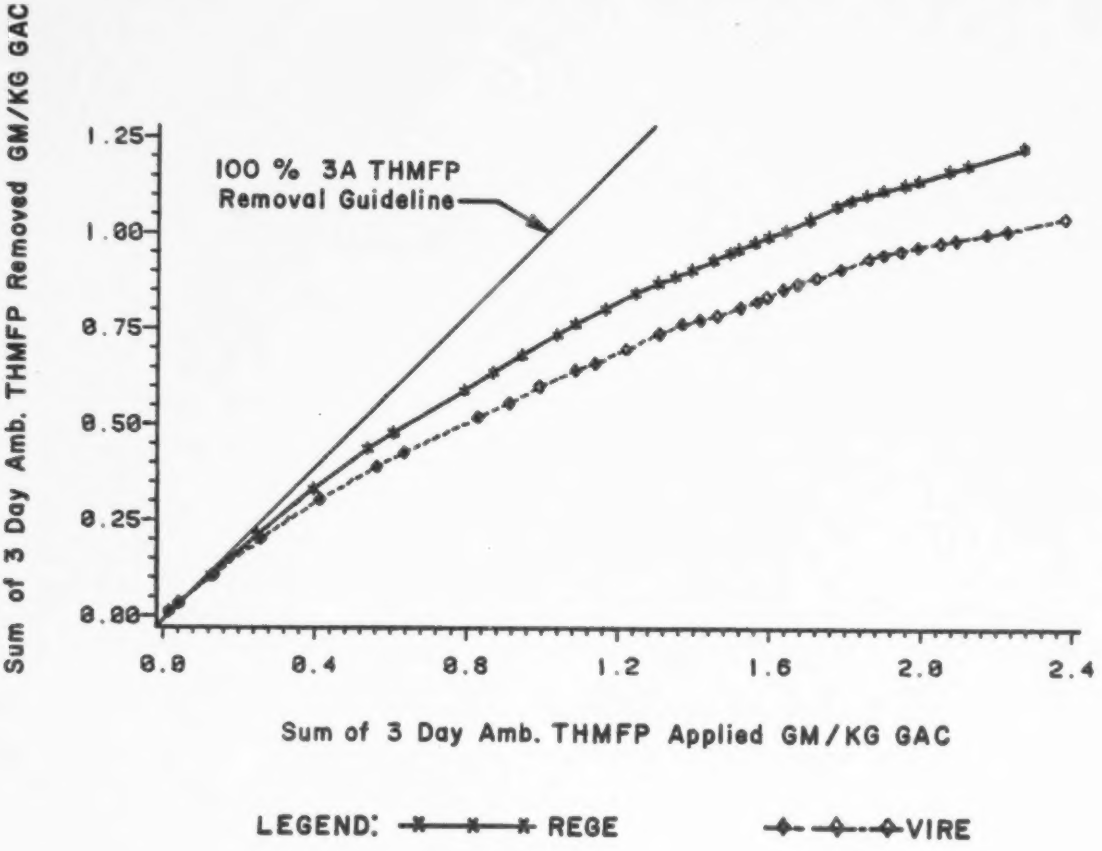


Figure B-10. Run 2.– 3 day amb. THMFP loading curves.

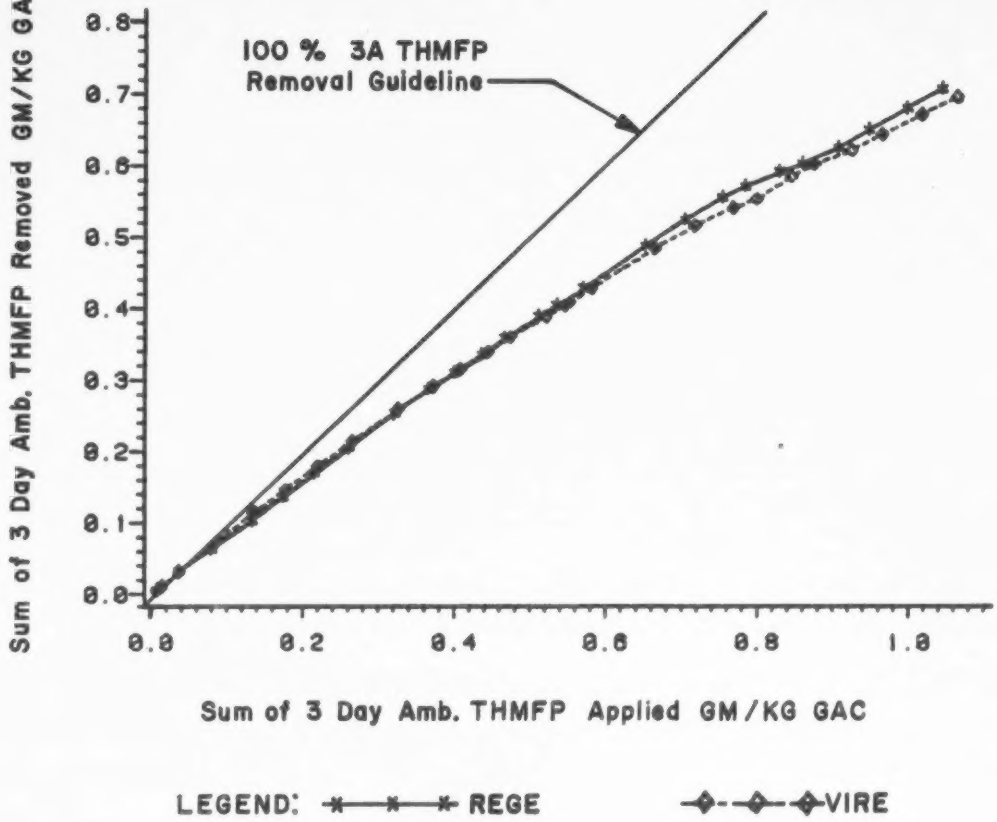


Figure B-11. Run 3.– 3 day amb. THMFP loading curves.

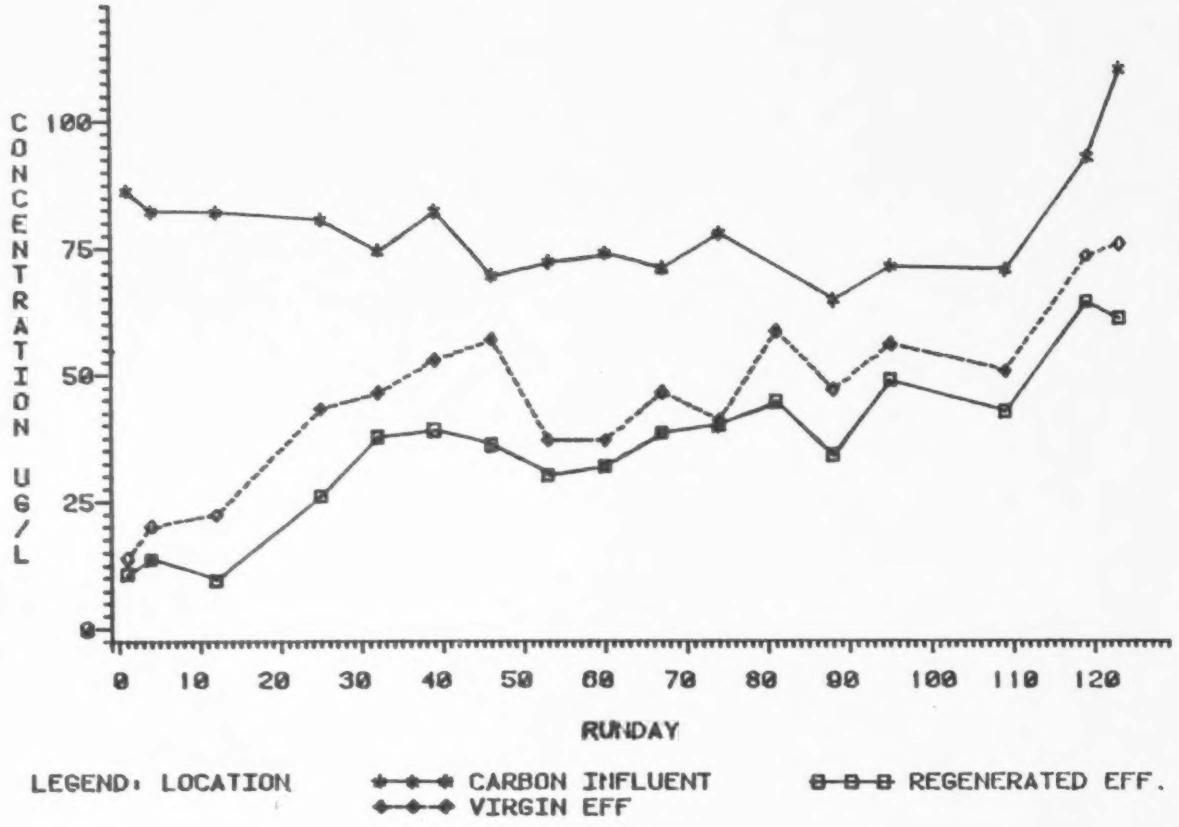


Figure B-12. Run I.- Seven day ambient THMFP breakthrough curves.

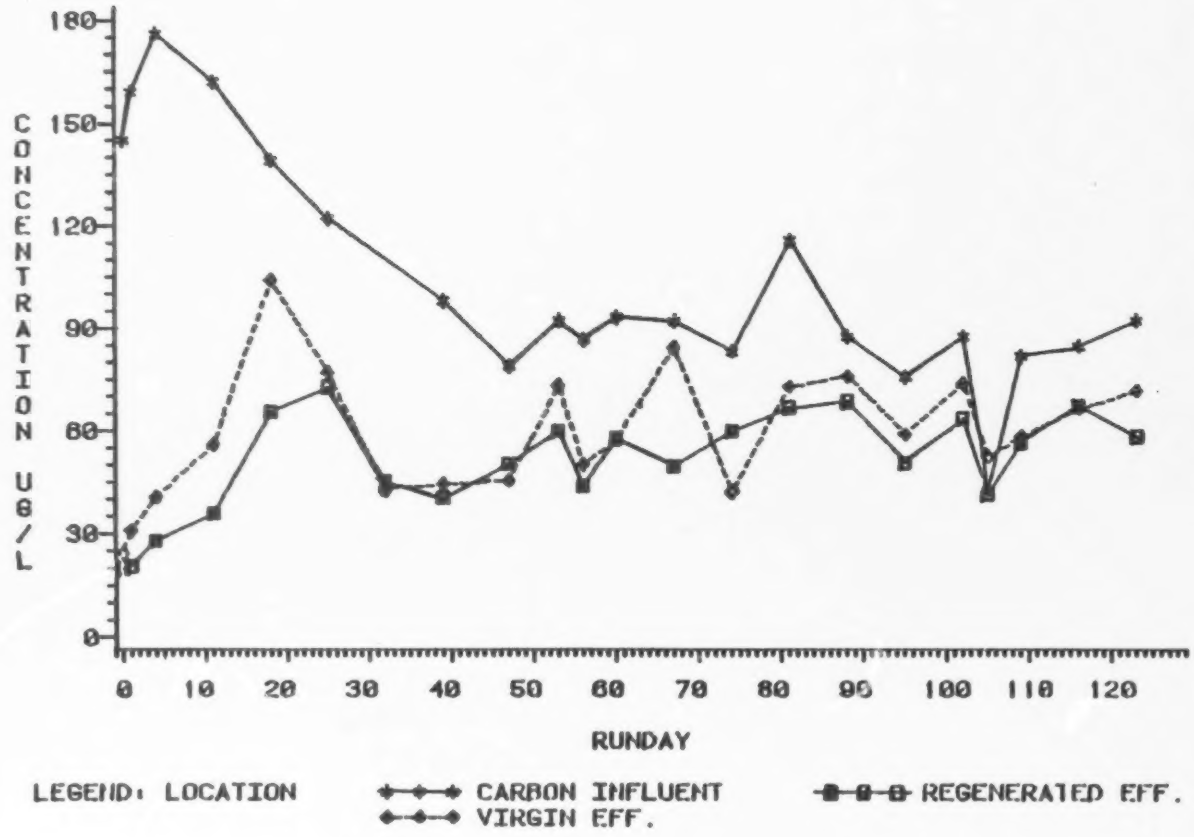


Figure B-13. Run 2.- Seven day ambient THMFP breakthrough curves.

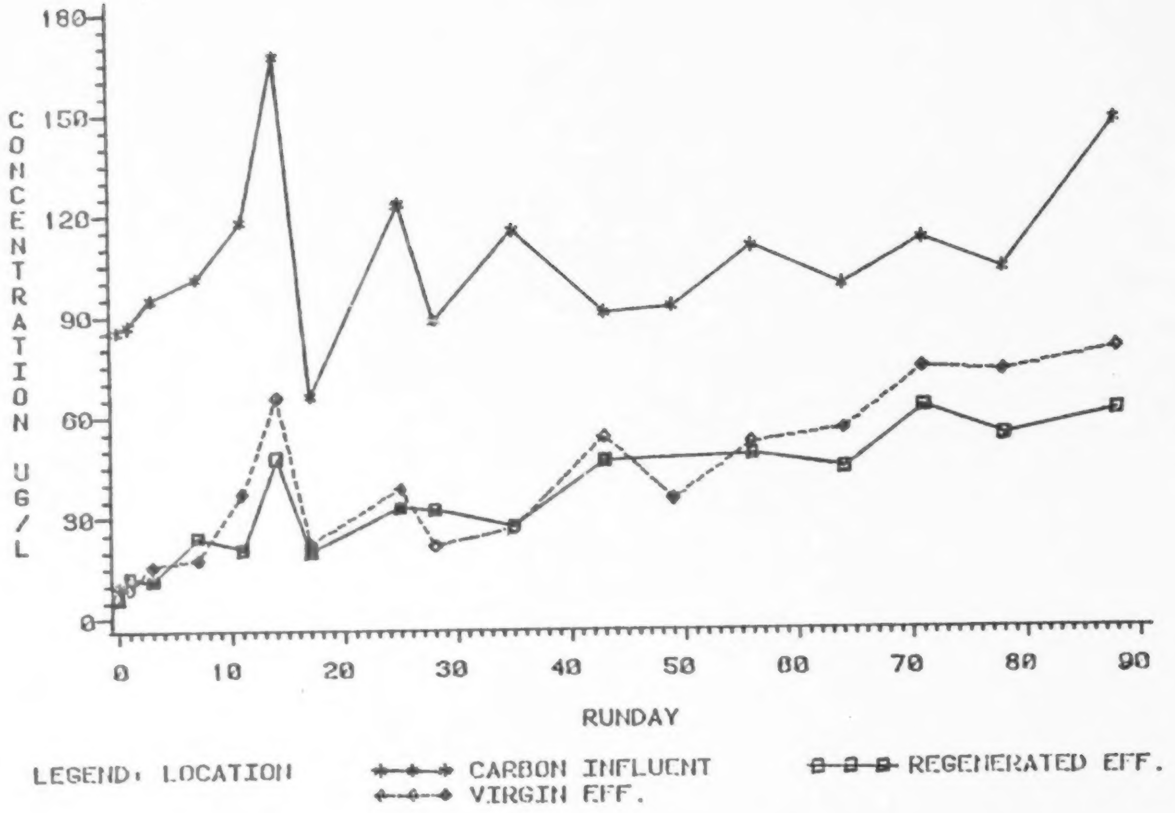


Figure B-14. Run 3.– Seven day ambient THMFP breakthrough curves.

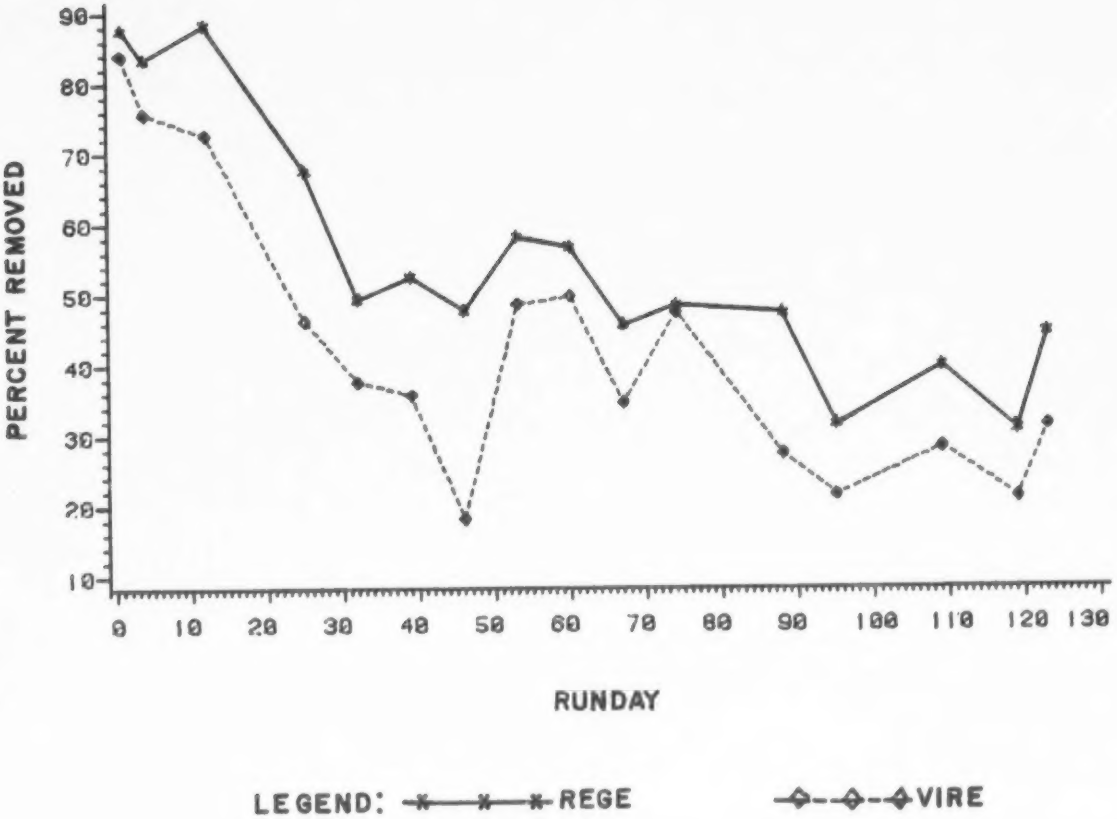


Figure B-15. Run I.-Percent removal 7 day amb. THMFP curves.

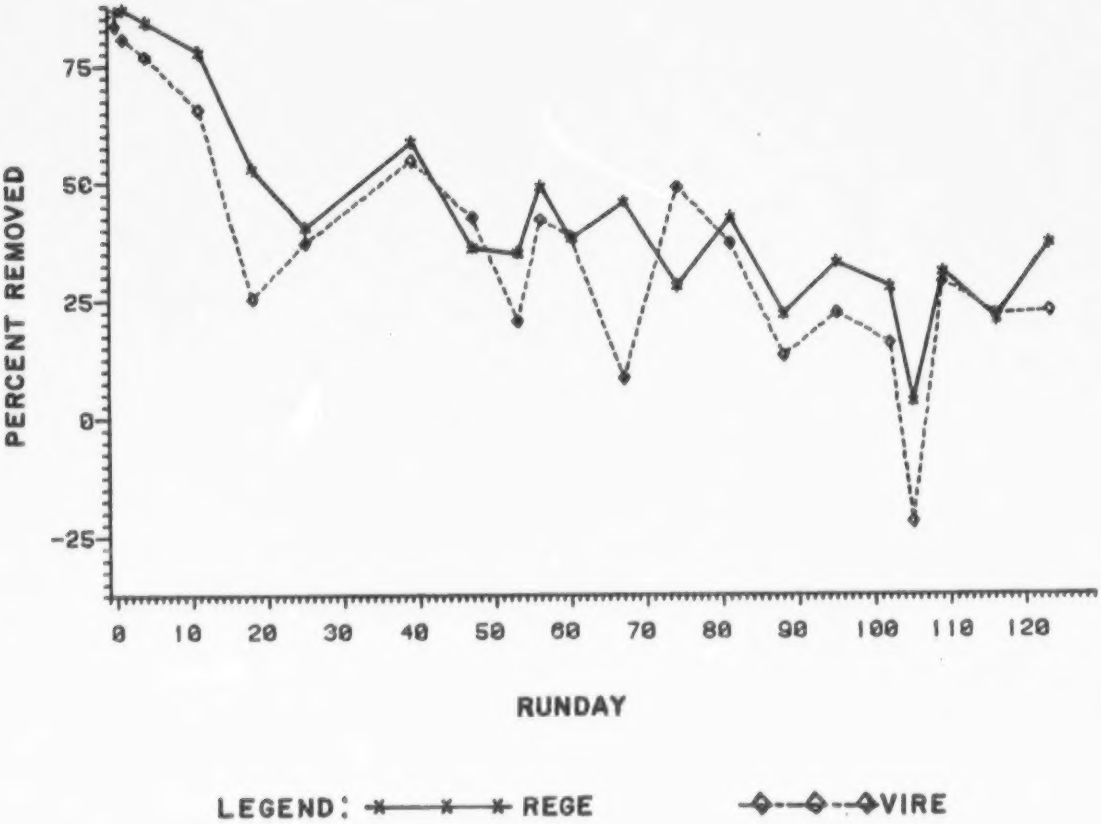


Figure B-16. Run 2.– Percent removal 7 day amb. THMFP curves.

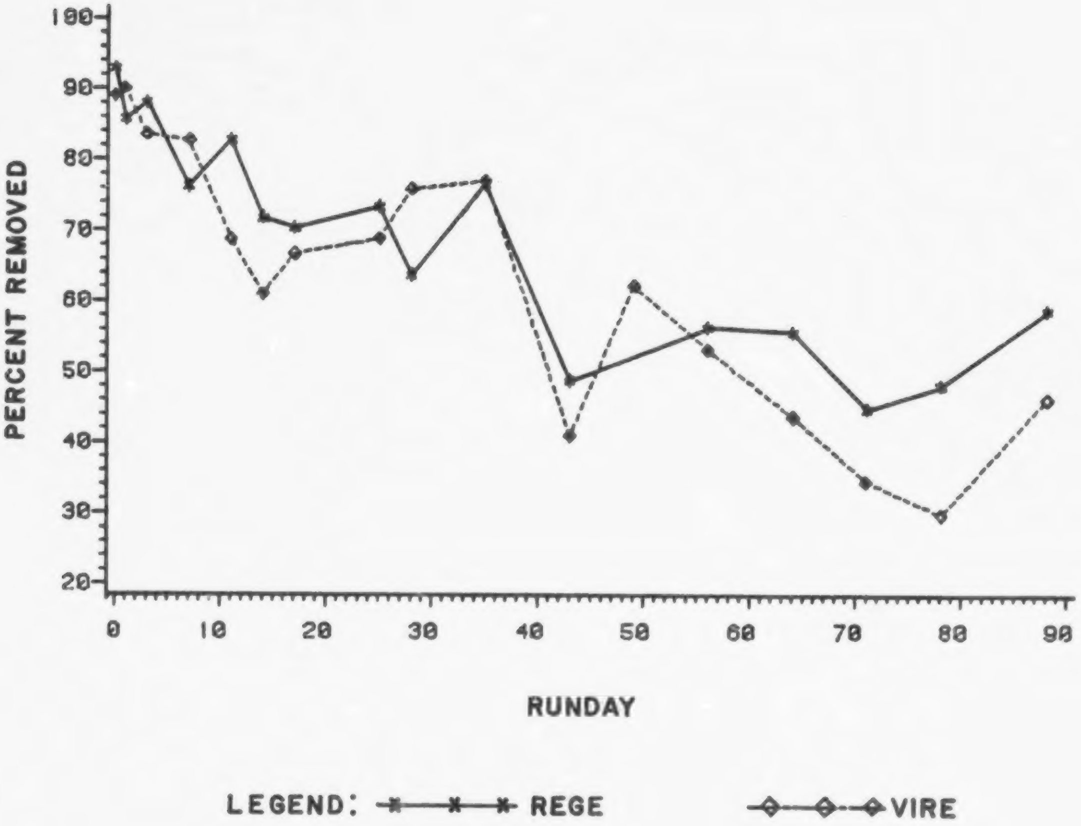


Figure B-17. Run 3.- Percent removal 7 day amb. THMFP curves.

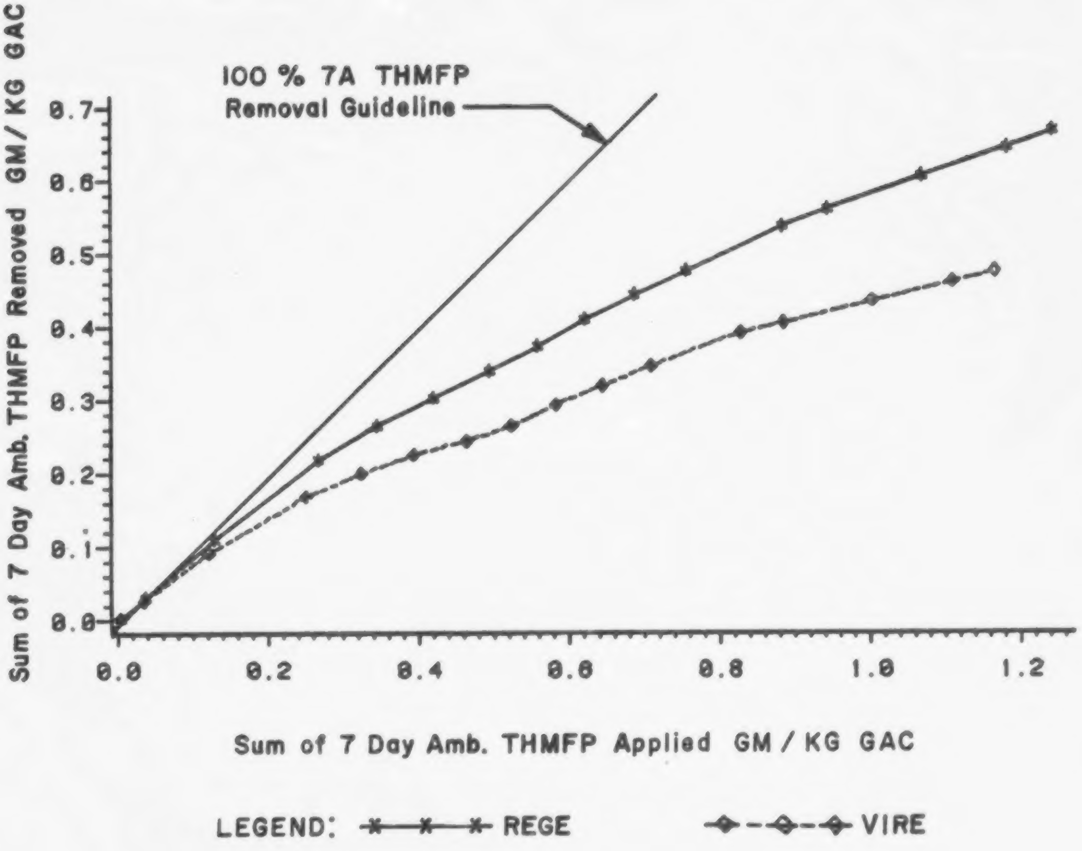


Figure B-18 Run I.—7 day amb. THMFP loading curves.

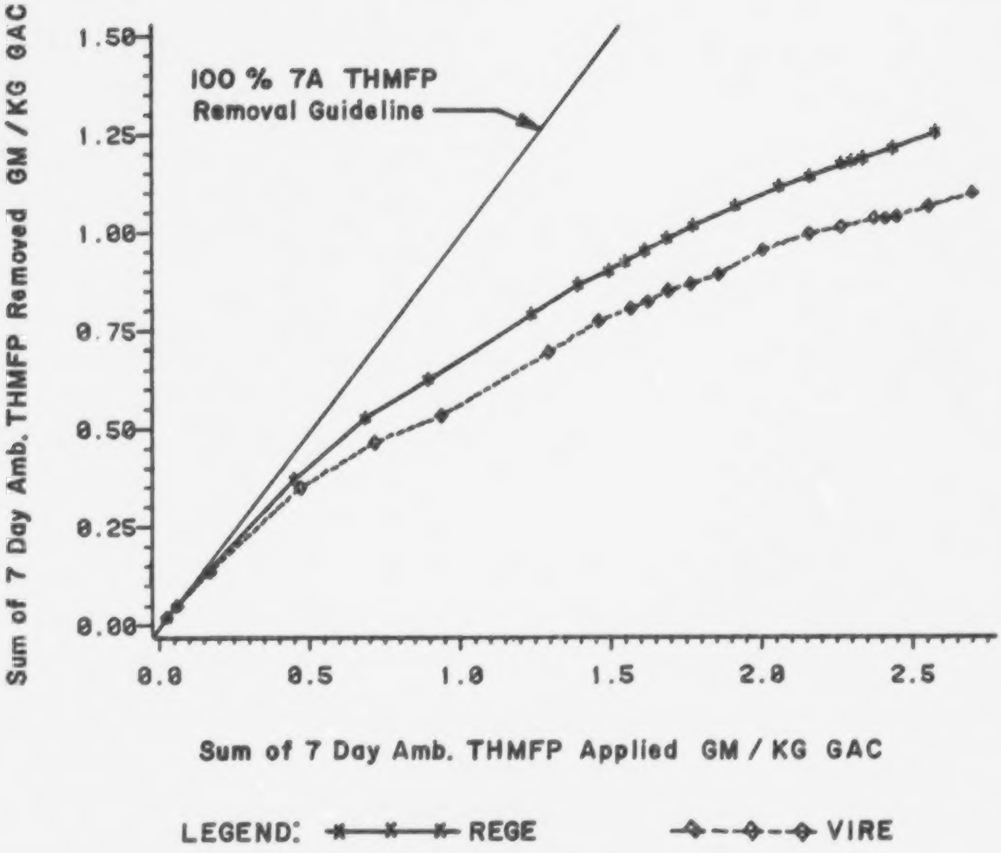


Figure B-19. Run 2.—7 day amb. THMFP loading curves.

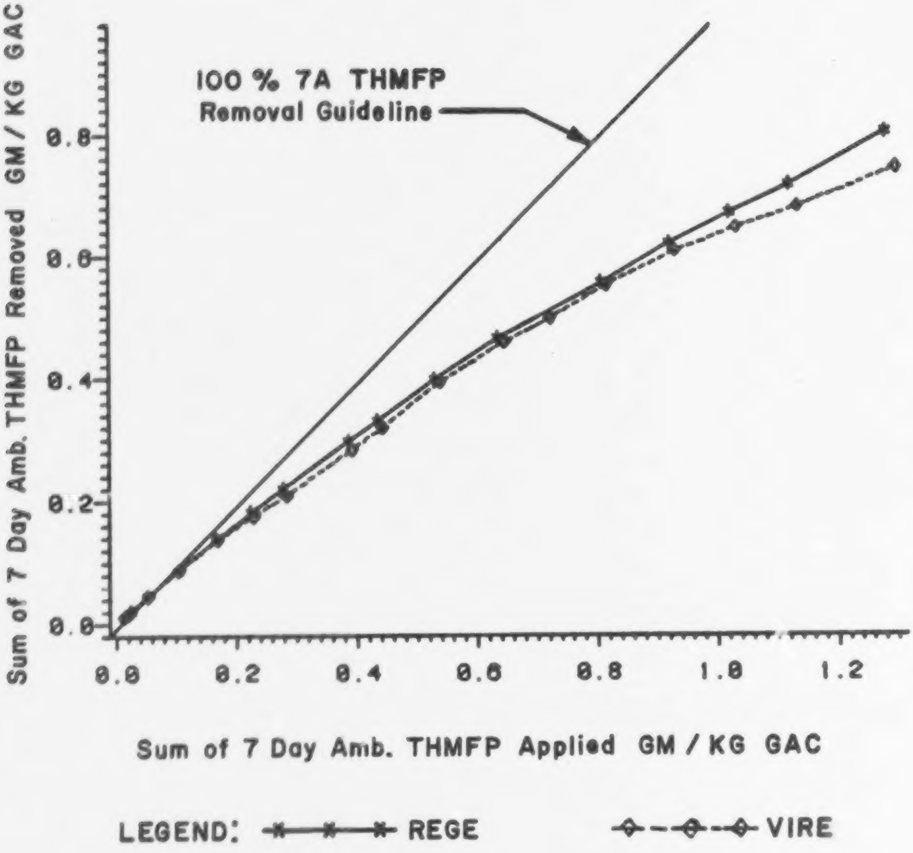


Figure B-20. Run 3.– 7 day amb. THMFP loading curves.

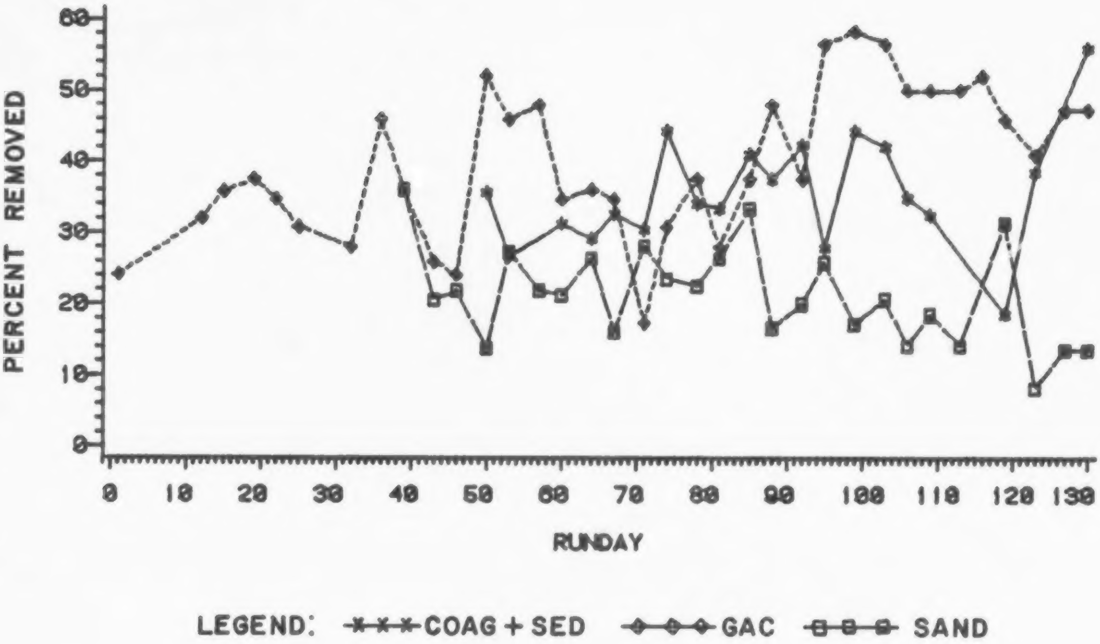


Figure B-21. Run I.- WTP process removal for TOC curves.

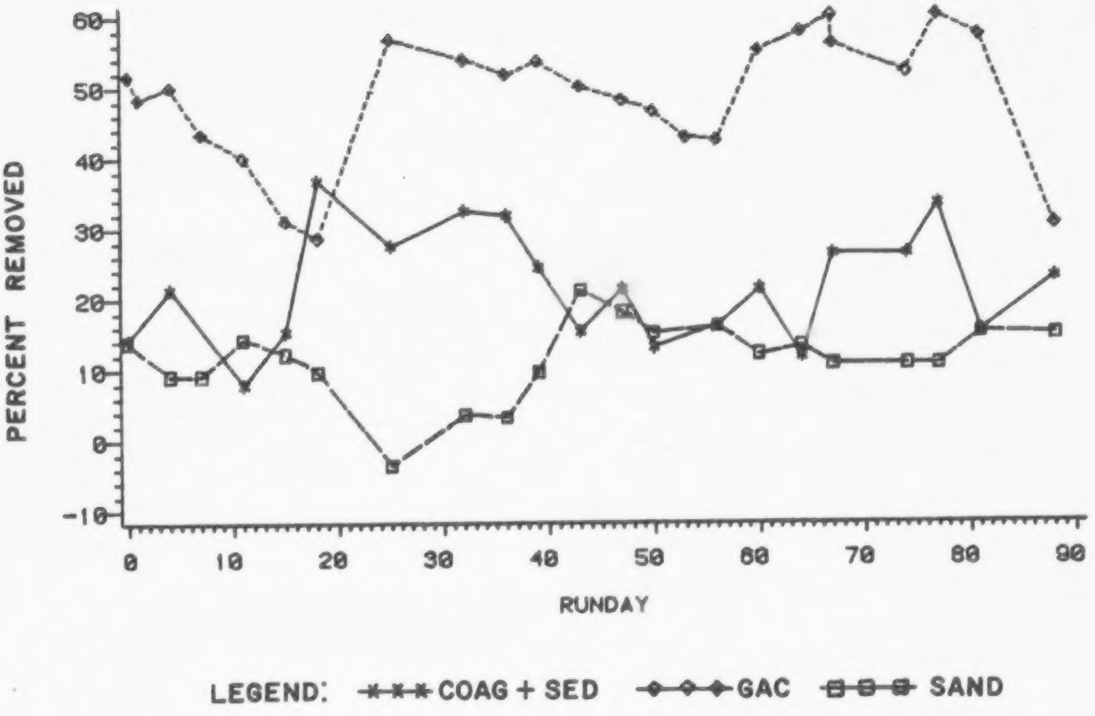


Figure B-22. Run 2.- WTP process removal for TOC curves.

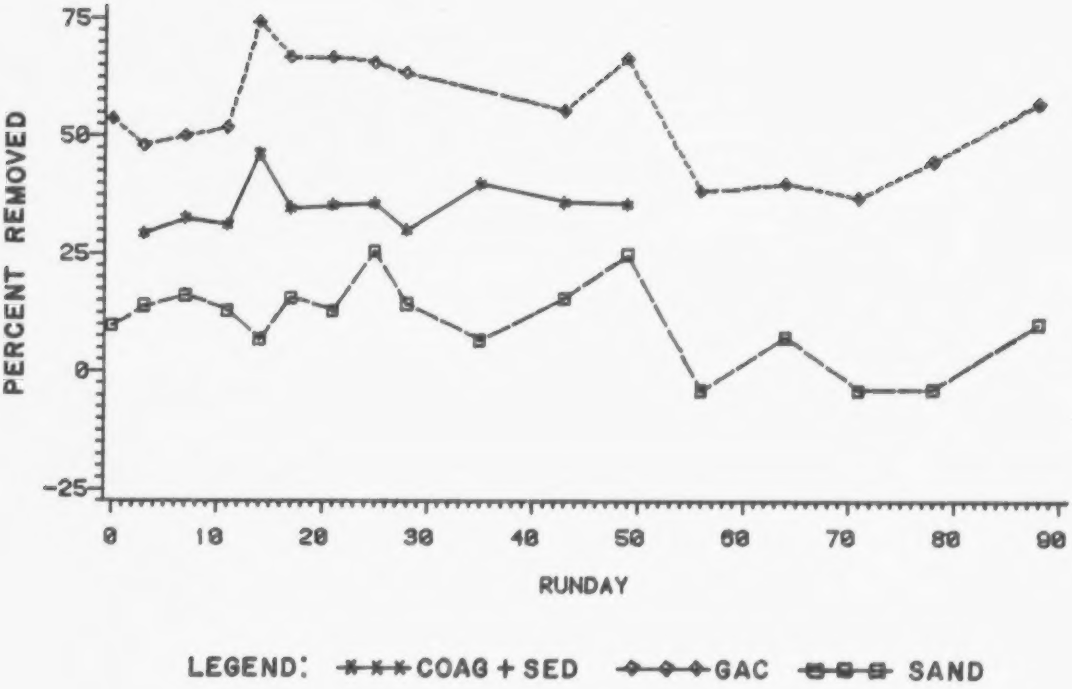


Figure B-23. Run 3.—WTP process removal for TOC curves.

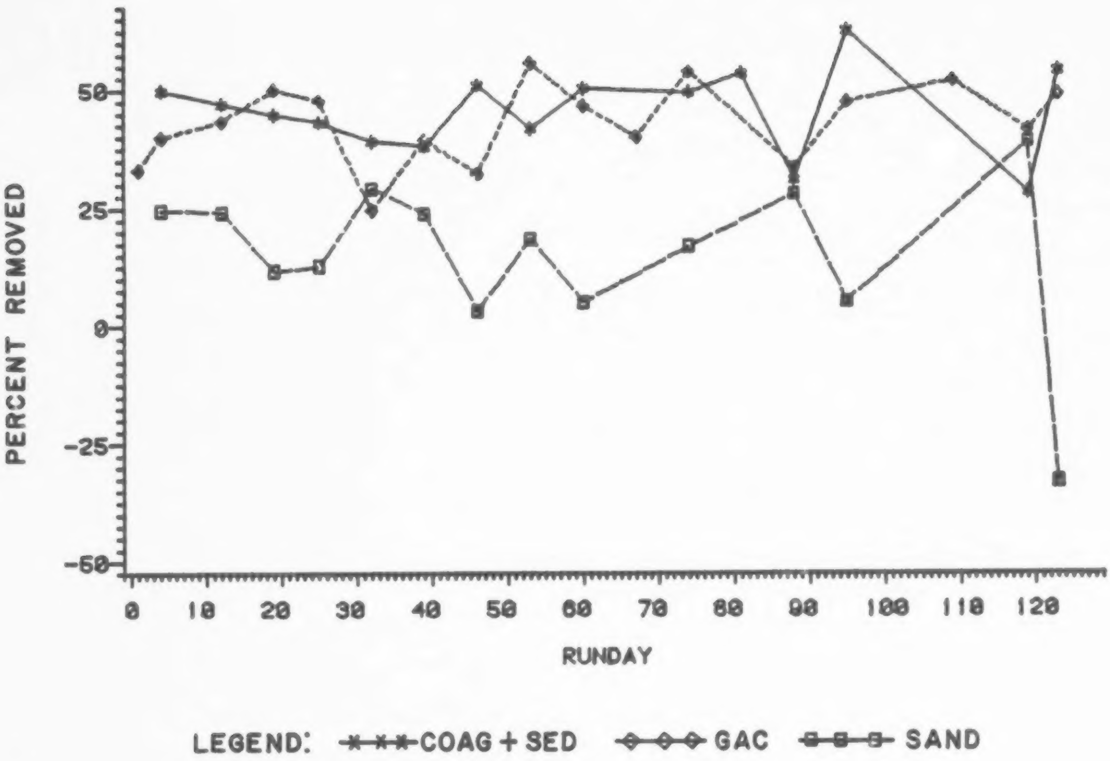


Figure B-24. Run I.— WTP process removal for 3 day amb. THMFP curves.

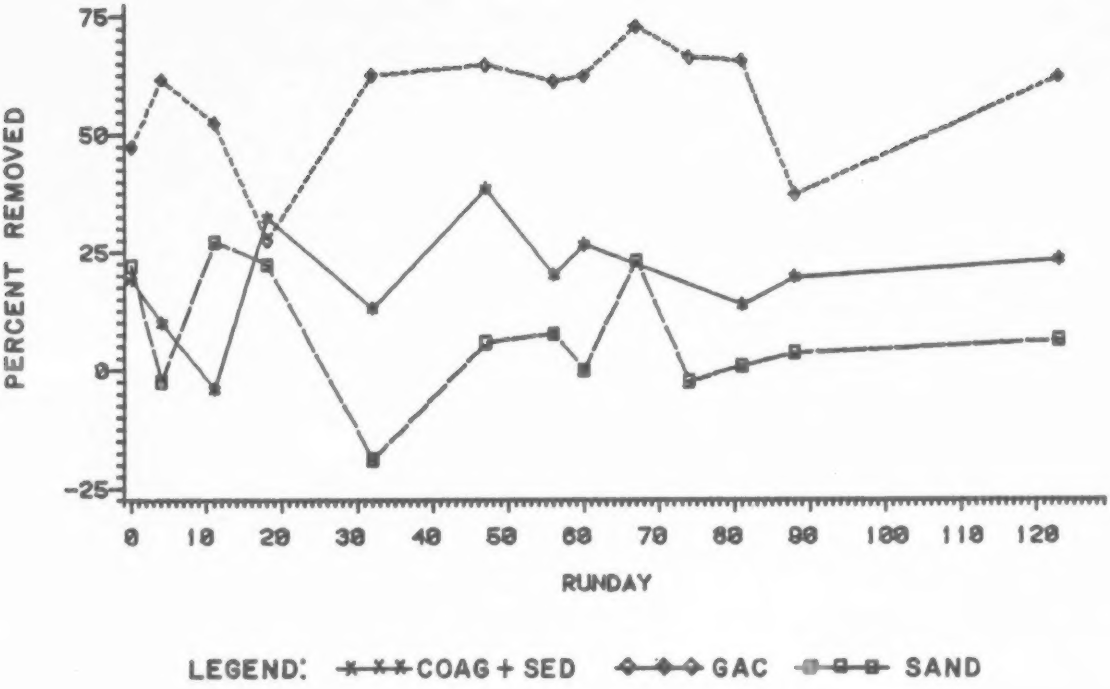


Figure B-25. Run 2.-WTP process removal for 3 day amb. THMFP curves.

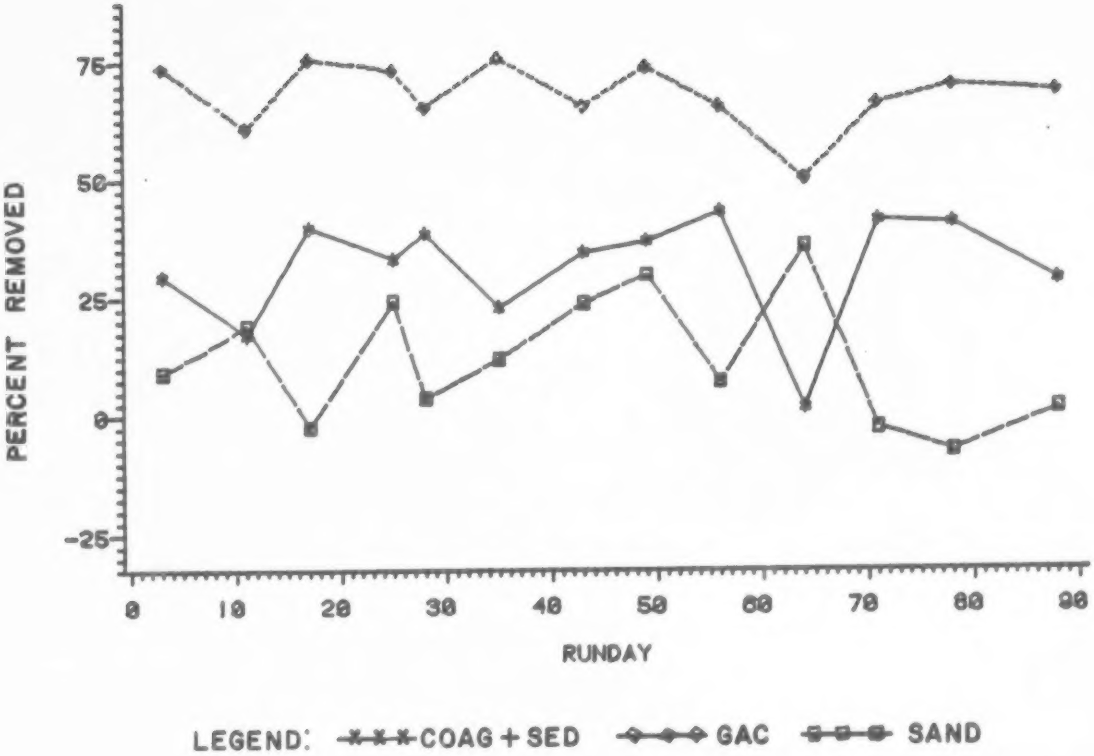


Figure B-26. Run 3.— WTP process removal for 3 day amb. THMFP curves.

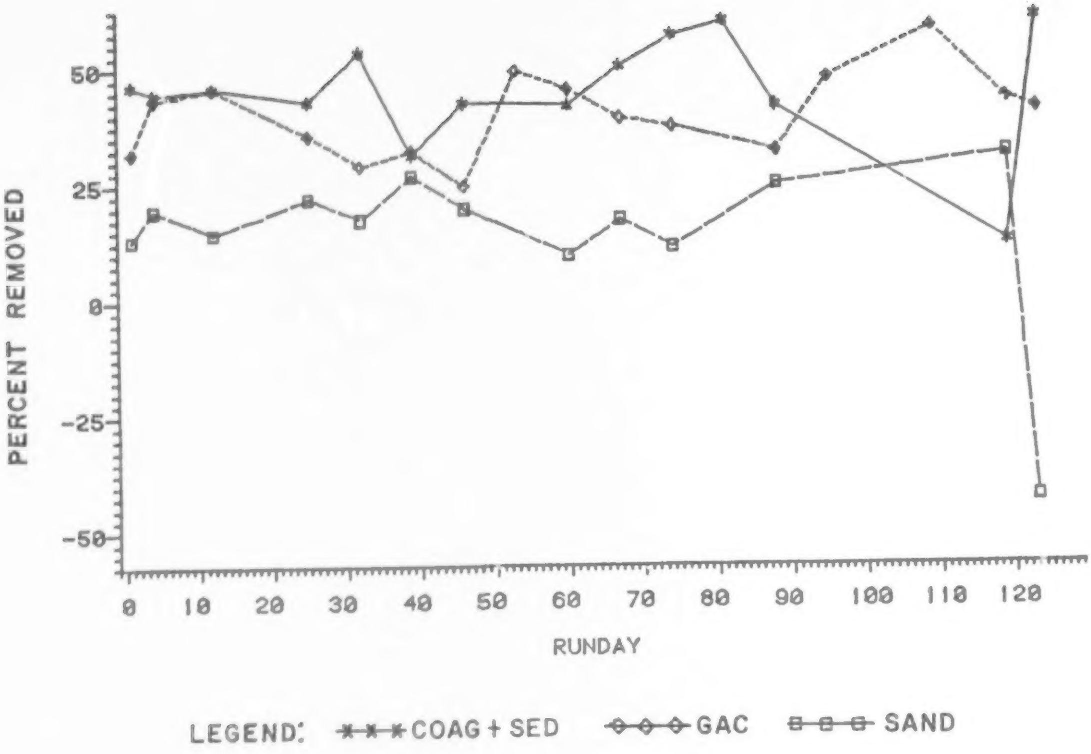


Figure B-27. Run I.–WTP process removal for 7 day amb. THMFP curves.

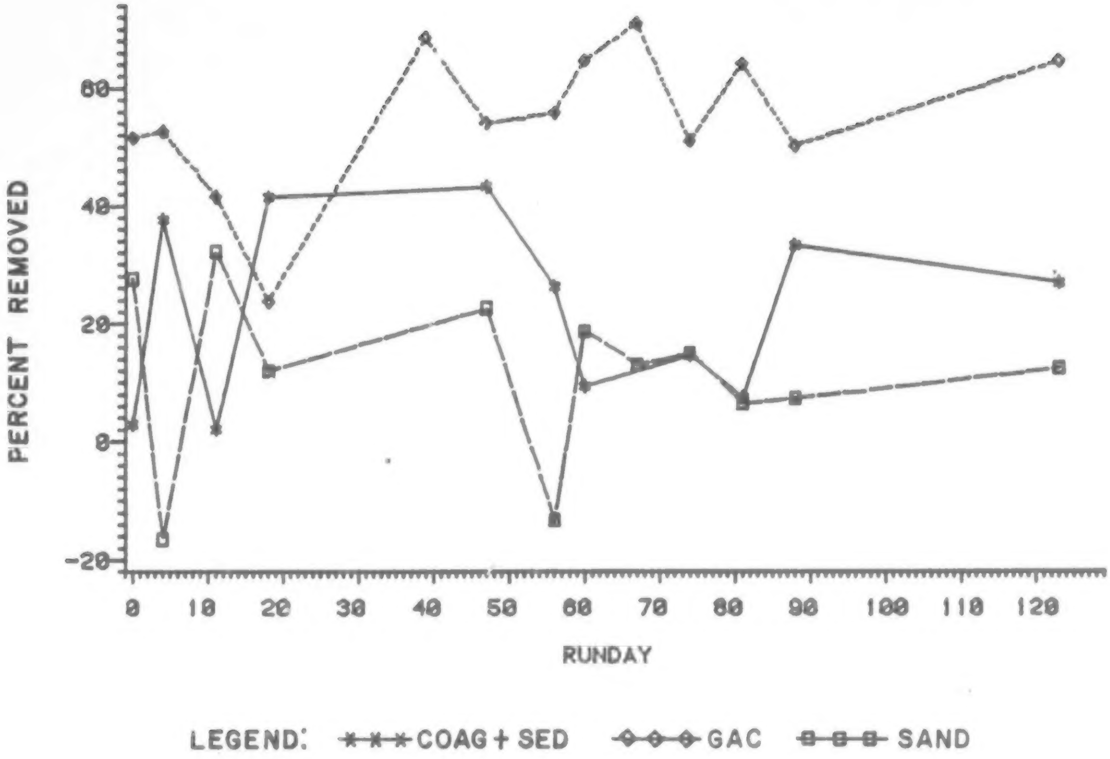


Figure B-28. Run 2.—WTP process removal for 7 day amb. THMFP curves.

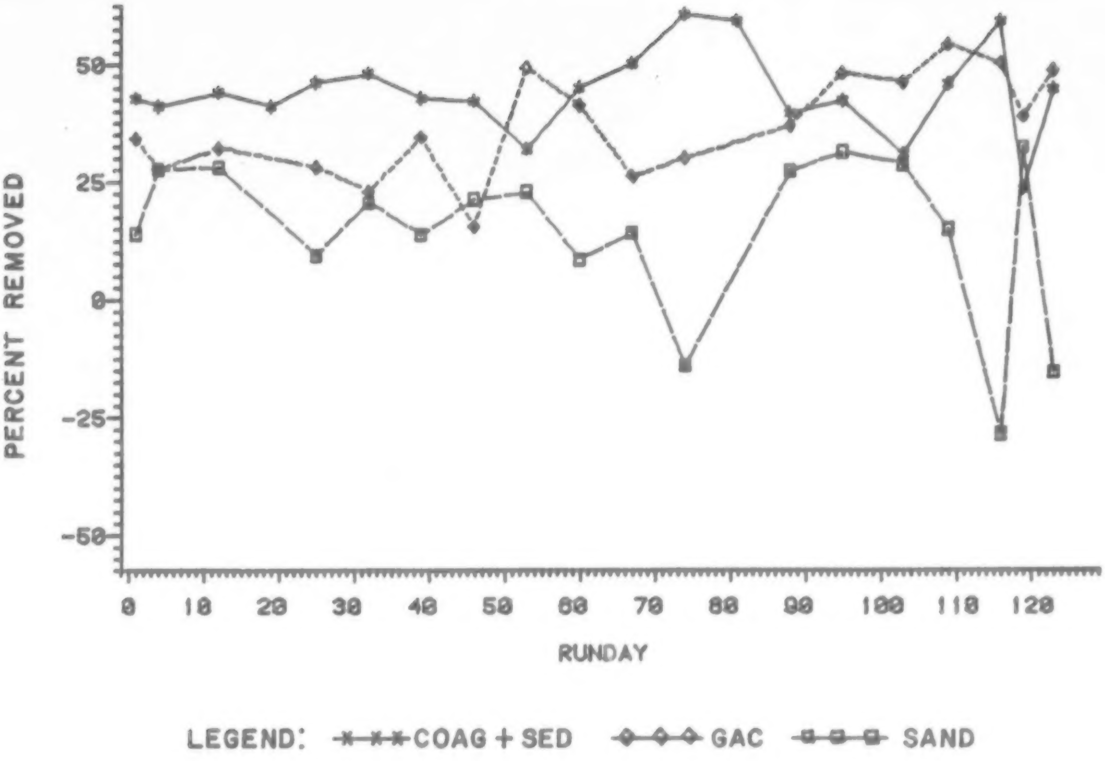


Figure B-29. Run I.—WTP process removal for 3 day max. THMFP curves.

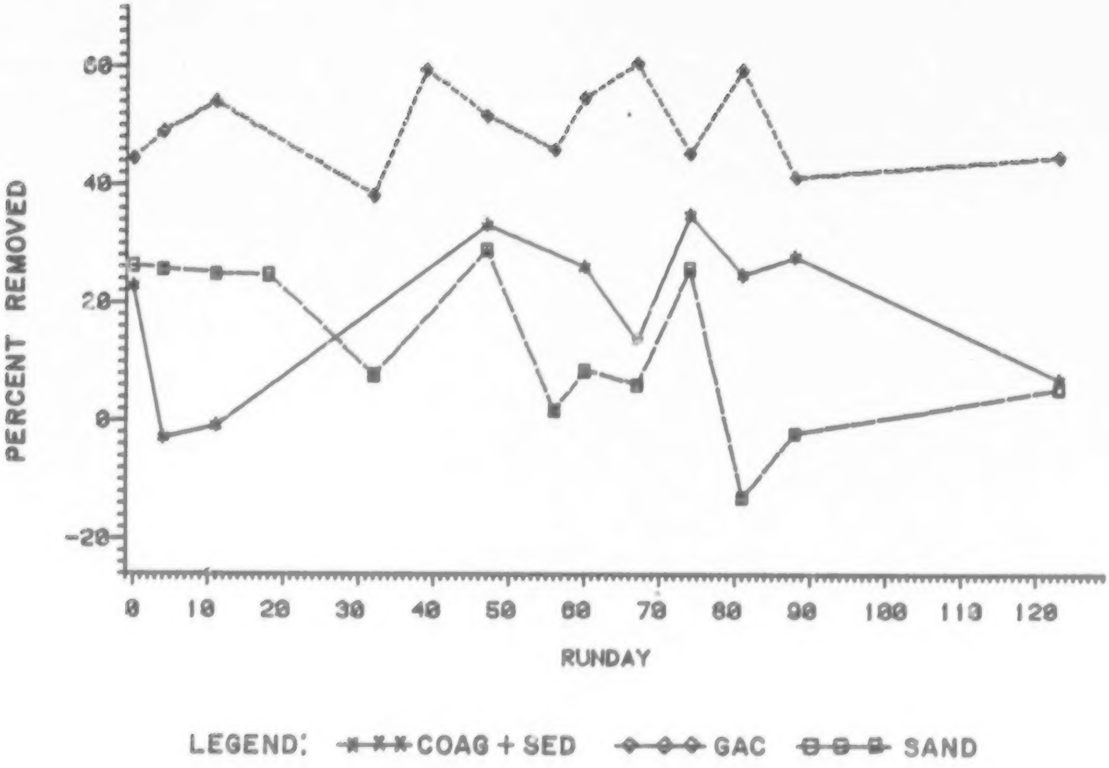


Figure B-30. Run 2.- WTP process removal for 3 day max. THMFP curves.

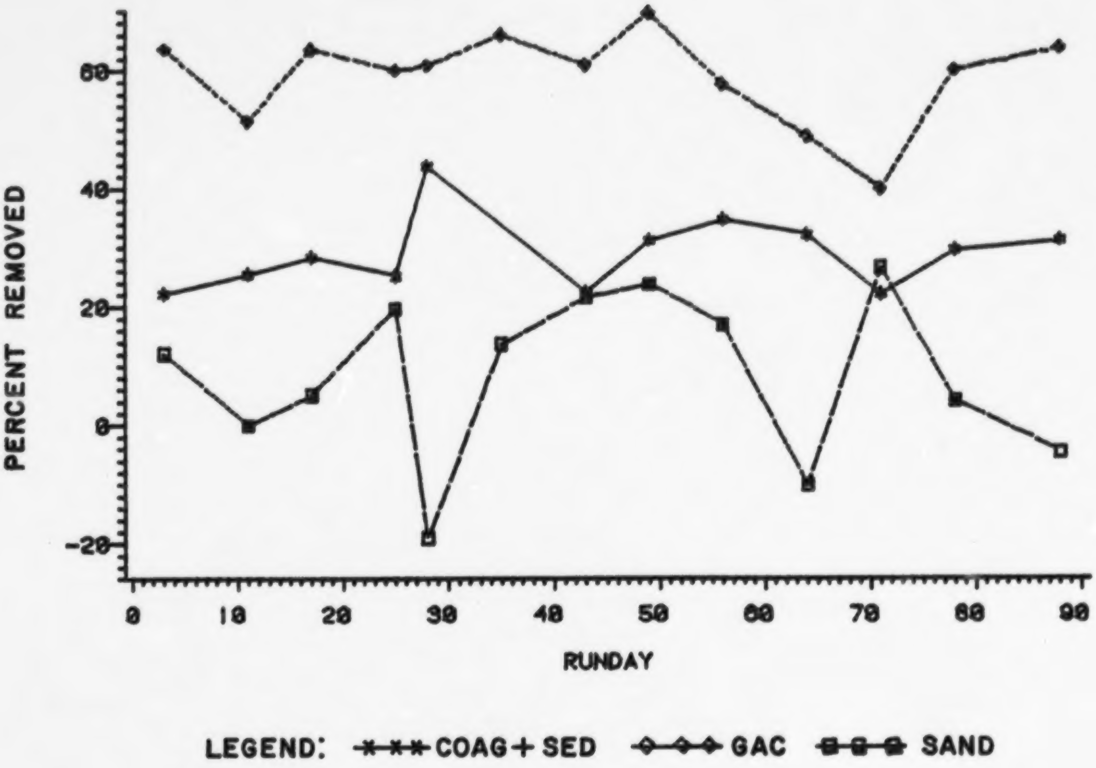


Figure B-31. Run 3.- WTP process removal for 3 day max. THMFP curves.

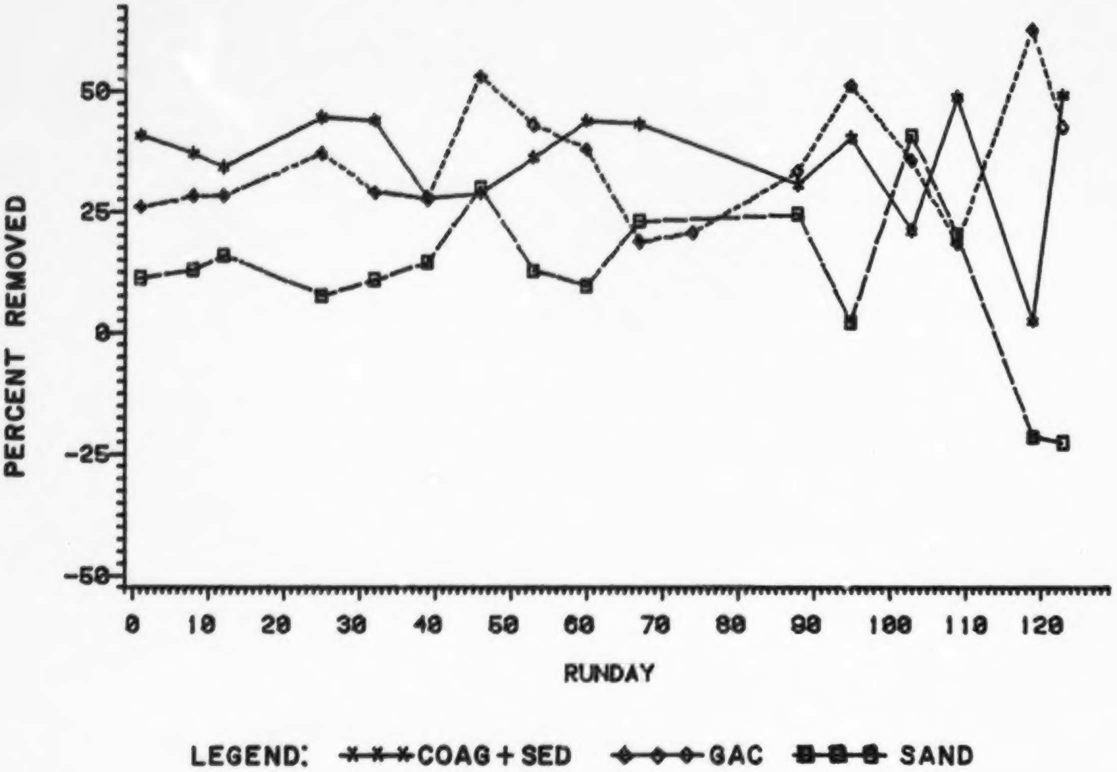


Figure B-32. Run I.- WTP process removal for 7 day max. THMFP curves.

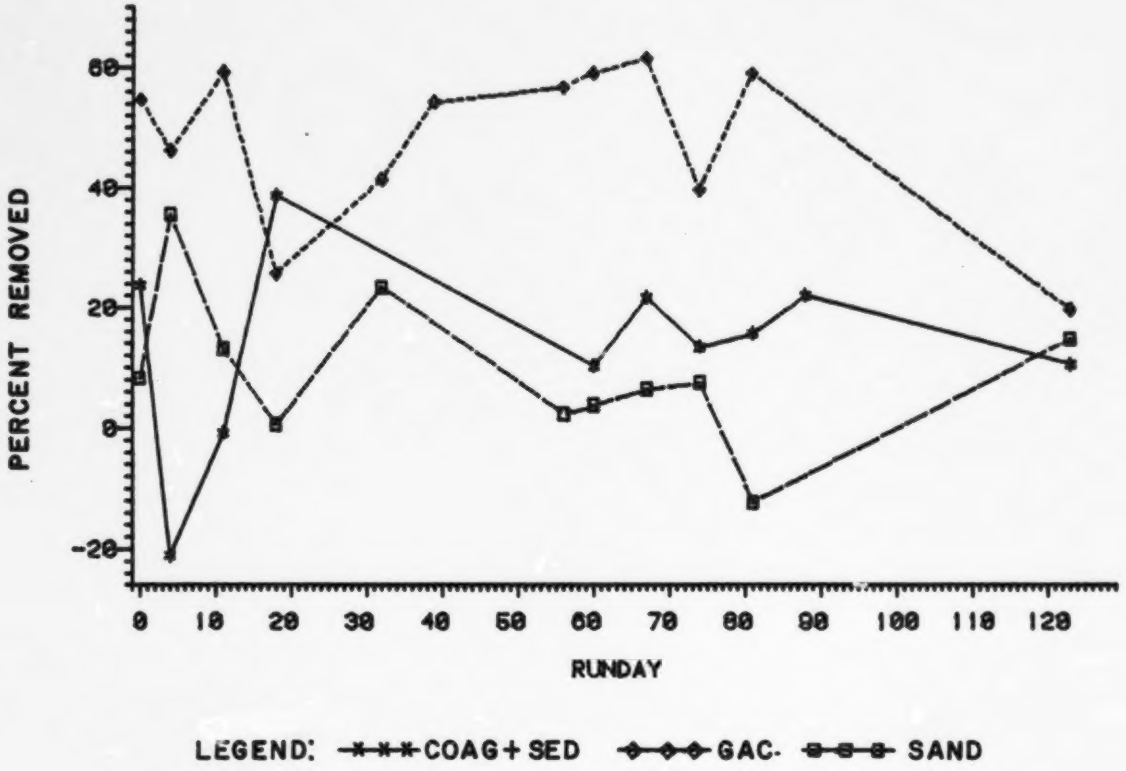


Figure B-33. Run 2.—WTP process removal for 7 day max. THMFP curves.

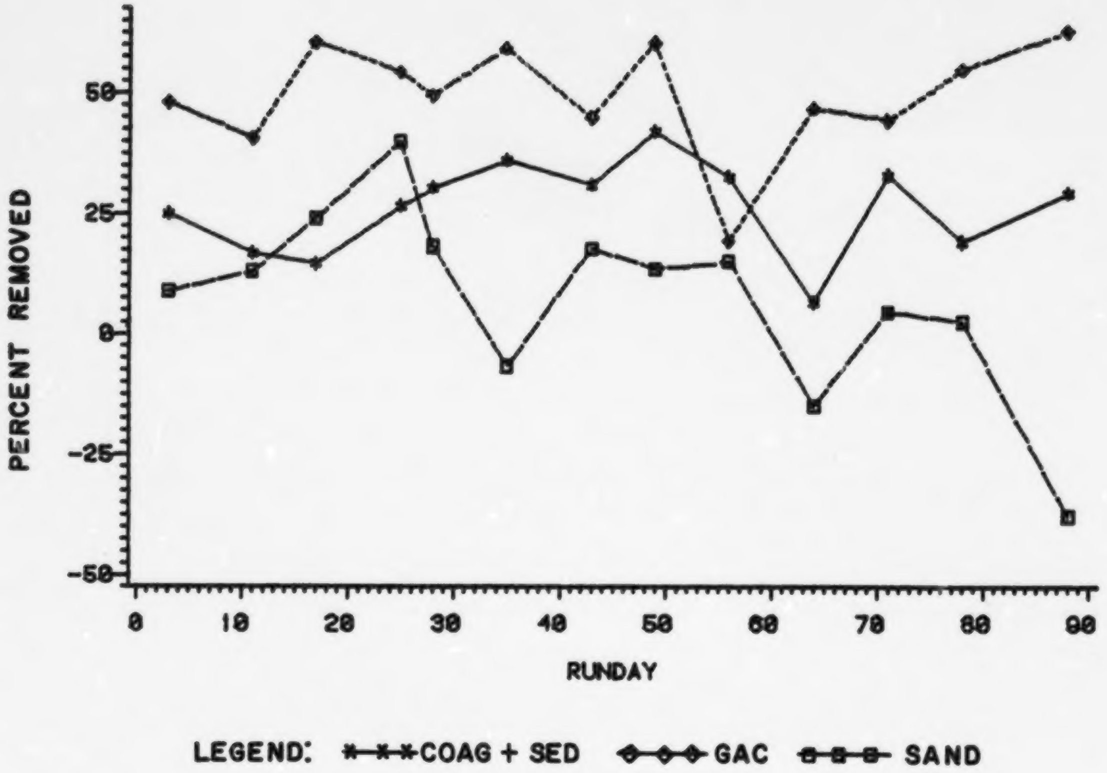


Figure B-34. Run 3.—WTP process removal for 7 day max. THMFP curves.

APPENDIX C

STATISTICAL ANALYSIS OF BREAKTHRU CURVES[1]

Graphical representations of virgin and reactivated GAC effluents have been plotted for selected parameters. The breakthru curves for TOC, chloroform, ITHM, 3-day TMA and 7-day TMA were subjected to a Gauss-Newton non-linear least squares regression analysis utilizing the so-called logistic function as a predictive model equation. In general form:

$$\text{Predicted Effluent} \quad y = \frac{C}{1 + Ke^{-Rt}} \qquad \text{(Eqn 1)}$$

where t = time in days and the coefficient K, C and R are solved for iteratively by curve fitting to the actual effluent concentrations versus runday (t).

As evidenced by the breakthru curve plots, the performance of reactivated GAC is qualitatively similar to virgin carbon. However, a distinguishable trend is seen with successive reactivations with the twice and thrice-reactivated curves tending toward coincidence.

To test the hypothesis that virgin and reactivated curves were "statistically" and quantitatively different, the following analyses were performed on each of the above-mentioned parameters (chemical constituents):

A) Virgin, once, twice and thrice reactivated effluent concentrations were plotted against runtime (in days).

B) The "best fit" curve was calculated for each effluent curve by the Gauss-Newton (Bard) algorithm.

C) The 3-curve fit coefficients (K, C and R) were computed along with their individual standard deviations.

D) A t-statistic (t-stat) was computed for each pair of virgin vs once reactivated, once vs twice reactivated and twice vs thrice reactivated K, C and R co-efficients.

E) In order to compare results between runs, the total loading curves were calculated and the percent sum removed vs runday curves were subjected to Gauss-Newton curve

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[1] John Ireland, Environmental Protection Agency.

E) Continued

fit using the same logistic function model system as in step B.

F. As in step D, a t-statistic was calculated for each pair of best fit model coefficient values, K, C and R.

In small-sampling theory (i.e., n $\leqq$ 30), the Student's t distribution is more appropriate that a standard normal distribution for significance and hypothesis testing. Proceeding from this argument, it was decided to investigate the null hypothesis H_O that if 2 samples of sizes N_1 and N_2 corresponding to virgin, once, twice or thrice reactivated carbon breakthru curve taken one pair at a time are drawn whose standard deviations in K, C and R coefficients will be equal if there is no quantitative difference in carbon type performance.

The percentile value (t_p) for the t-distribution with between 60 and 120 degrees of freedom (average 72 for all cases studied here) were found for 0.01 and 0.05 levels of significance;

at 0.01 level of significance $t_{.995} = 2.66$

at 0.05 level of significance $t_{.975} = 2.00$

Hence, if the null hypothesis H_O is false, i.e., the carbon performances are statistically different, the computed t-statistic will exceed the percentile values given above.

Table C-1 reports all calculated K, C and R coefficients for non-linear step E) regressions and the calculated t-statistics (t-stat, step F) for percent sum removed vs runday data.

Results of Statistical Testing

It is apparent from visual observation of the plotted loading curves that the model equation provides an accurate curve fit to the actual data in all cases. The statistical analysis performed on the best fit model coefficients indicates that there is essentially no differnce between K and R coefficient values within runs for all analyses tested. However, large statistical differences are seen in the C coefficient values both within and between runs. These C values do tend toward coincidence in run 3 for all analytes tested. This approach to coincidence is also verified visually in the plots (both actual and predicted) of sum removed vs runday, i.e., the plots are nearly superimposable.

In all cases it can be seen the carbon reactivated the

TABLE C-1

CALCULATED MODEL FUNCTION PARAMETERS

Run	Description	K	C	R
TOC				
1	Virgin$_A$ nonlin	7.91	0.0148	0.0390
	Std. dev.	0.90	0.0005	0.0030
	N = 36			
	Regen1$_B$ nonlin	7.52	0.0210	0.0387
	Std. dev.	0.73	0.0006	0.0026
	N = 36			
	t-stat	1.99	46.9	0.447
	Std. Dev. = 0.137			
2	Regen1$_A$ nonlin	8.75	0.015	0.118
	Std. dev.	1.48	0.0006	0.012
	N = 20			
	Regen2$_B$ nonlin	9.77	0.0171	0.120
	Std. dev.	1.69	0.0007	0.012
	N = 21			
	t-stat	2.00	10.0	0.520
	Std. Dev. = 0.0185			
3	Regen2$_A$ nonlin	11.17	0.0171	0.0689
	Std. dev.	1.55	0.0005	0.0051
	N = 32			
	Regen3$_B$ nonlin	10.43	0.0175	0.0652
	Std. dev.	1.56	0.0006	0.0056
	N = 31			
	t-stat	1.85	2.8	2.7
	Std. Dev. = 0.0005			

Table C-1 Continued

Run	Description	K	C	R
Chloroform				
1	Virgin$_A$ nonlin	10.37	0.0321	0.0840
	Std. Dev.	2.2	0.0005	0.0073
	N = 36			
	Regen1$_B$ nonlin	10.91	0.0414	0.0781
	Std. Dev.	2.0	0.0006	0.0058
	N = 36			
	t-stat	1.07	70.4	3.74
	Std. Dev. = 0.150			
2	Regen1$_A$ nonlin	5.958	0.0718	0.0897
	Std. Dev.	1.08	0.006	0.015
	N = 21			
	Regen2$_B$ nonlin	6.66	0.0807	0.0845
	Std. Dev.	1.13	0.008	0.013
	N = 22			
	t-stat	2.03	4.02	1.19
	Std. Dev. = 0.060			
3	Regen2$_A$ nonlin	12.65	0.0738	0.0889
	Std. Dev.	2.12	0.0016	0.0066
	N = 32			
	Regen3$_B$ nonlin	12.53	0.0730	0.0882
	Std. Dev.	2.18	0.0017	0.0069
	N = 32			
	t-stat	0.22	1.91	0.408
	Std. Dev. = 0.00067			

Table C-1 Continued

Run	Description	K	C	R
ITHM				
	Virgin$_A$ nonlin	12.36	0.0378	0.0904
	Std. Dev.	2.36	0.0005	0.0065
	N = 36			
1	Regen1$_B$ nonlin	10.37	0.0500	0.0739
	Std. Dev.	1.89	0.0007	0.0055
	N = 36			
	t-stat	3.89	83.9	11.5
	Std. Dev. = 0.209			
	Regen1$_A$ nonlin	7.27	0.0977	0.0953
	Std. Dev.	1.15	0.0065	0.0120
	N = 21			
2	Regen2$_B$ nonlin	7.93	0.106	0.0921
	Std. Dev.	1.22	0.0076	0.011
	N = 22			
	t-stat	1.78	3.75	0.89
	Std. Dev. = 0.0447			
	Regen2$_A$ nonlin	12.35	0.0858	0.0868
	Std. Dev.	3.148	0.0019	0.0065
	N = 32			
3	Regen3$_B$ nonlin	11.89	0.0842	0.0855
	Std. Dev.	2.04	0.0021	0.0068
	N = 32			
	t-stat	0.68	3.14	0.769
	Std. Dev. = 0.0022			

Table C-1 Continued

Run	Description	K	C	R
THREE-DAY TMA				
	Virgin$_A$ nonlin	6.45	0.417	0.0416
	Std. Dev.	0.65	0.012	0.0030
	N = 33			
1	Regen1$_B$ nonlin	7.01	0.634	0.0386
	Std. Dev.	0.73	0.024	0.0030
	N = 32			
	t-stat	3.2	45.6	3.97
	Std. Dev. = 4.75			
	Regen1$_A$ nonlin	7.33	0.721	0.125
	Std. Dev.	1.62	0.029	0.017
	N = 15			
2	Regen2$_B$ nonlin	8.04	0.827	0.127
	Std. Dev.	1.79	0.032	0.016
	N = 15			
	t-stat	1.10	9.18	0.32
	Std. Dev. = 1.08			
	Regen2$_A$ nonlin	8.83	0.685	0.0579
	Std. Dev .	1.17	0.026	0.0051
	N = 26			
3	Regen3$_B$ nonlin	9.54	0.695	0.0588
	Std. Dev.	1.2	0.025	0.0048
	N = 26			
	t-stat	2.1	1.38	0.642
	Std. Dev. = 0.0102			

Table C-1 Continued

Run	Description	K	C	R
SEVEN-DAY TMA				
1	Virgin$_A$ nonlin	7.09	0.468	0.0428
	Std. Dev.	1.4	0.022	0.0054
	N = 16			
	Regen1$_B$ nonlin	7.77	0.652	0.0439
	Std. Dev.	1.55	0.029	0.0053
	N = 16			
	t-stat	1.26	19.6	0.56
	Std. Dev. = 3.879			
2	Regen1$_A$ nonlin	8.02	0.734	0.1424
	Std. Dev.	3.09	0.051	0.030
	N = 8			
	Regen2$_B$ nonlin	9.30	0.827	0.1524
	Std. Dev.	3.29	0.046	0.027
	N = 8			
	t-stat	0.75	3.58	0.655
	Std. Dev. = 0.874			
3	Regen2$_A$ nonlin	9.32	0.711	0.0667
	Std. Dev.	1.44	0.028	0.063
	N = 17			
	Regen3$_B$ nonlin	9.26	0.763	0.0633
	Std. Dev.	1.65	0.039	0.0076
	N = 16			
	t-stat	0.108	4.28	0.208
	Std. Dev. = 0.163			

greater number of times ($_A$) adsorbs more over a given runtime than the corresponding carbon with one less reactivation ($_B$). However, by run 3 the difference in sum removed between twice and thrice reactivated carbon is negligible.

The overall results can be discussed conveniently by considering one analyte (CCl_3) as a general example. Of particular interest are the C values reported across runs. The values of C represent the final predicted equilibrium percent removed. Comparing run 1 with run 2, one sees that the value of C has increased by more than a factor of 2. This is generally true for the other 4 analytes tested. Going from run 2 to run 3 the values of C increase only slightly. The same result is seen for TOC although the values actually decrease slightly for ITHM, 3-day TMB and 7-day TMA. These facts suggest that a nearly twofold increase in ultimate carbon adsorption capacity is seen with a single reactivation. However, another reactivation does not seem to result in any appreciable increase in capacity.

To verify that the adsorption capacity had actually increased between runs 1 and 2, the average analyte influent concentration was calculated for each run.

TABLE C-2

AVERAGE INFLUENT CONCENTRATION VALUES ACROSS RUNS

Analyte	Run	Avg. Influent Conc. (μ g/1)
TOC	1	2.43
	2	2.77
	3	2.76
CCl_3	1	6.17
	2	8.94
	3	5.42
ITHM	1	10.54
	2	11.75
	3	8.67
3-DAY TMA	1	67.41
	2	92.20
	3	85.90
7-DAY TMA	1	78.74
	2	104.8
	3	105.8

This data displays the fact that the influent concentration fluctuates very little between runs for TOC, CCl_3 and ITHM and would not account for any large variations in the final equilibrium percent sums removed (e.g., carbon capacity). In other words, adsorption "driving-force" is not increased by an increased influent concentration between runs for any of these analytes. In contrast, the increase in influent concentration from run 1 to run 2 for 3 and 7-day TMA is somewhat larger which prohibits ignoring this situation in evaluation of apparent capacity increase.

In the model equation, values of the C coefficient represent final equilibrium concentration values for the breakthru curves. The values of the R coefficient represents a rate change of concentration factor. Values of the K coefficient most likely contain dependencies on several parameters including carbon type, analyte, percent loading and hydraulics. An analytical expression for K in terms of these parameters has not yet been worked out. It is apparent from visual observation of the plotted breakthru curves, however, that the model equation provides an accurate curve fit to the actual data in all cases. A more rigorous description of the model equation and the physical significance of its parameters is currently in preparation.

From a strictly empirical point of view, the present logistic function model as applied to effluent loading provides quantitative information about GAC adsorption capacity. With relatively simple statistical methods, it is possible to demonstrate that limited reactivation of spent virgin GAC results in substantial apparent adsorption capacity increase.

Tests of Hypotheses and Significance for Small Samples

A. Difference of Means or Estimators

Suppose that 2 random samples of size N_1 and N_2 are drawn from normal populations whose standard deviations are equal ($o_1 = o_2$). Suppose further that these 2 samples have means and standard deviations given by X_1, X_2 and s_1, s_2, respectively. To test the hypothesis H_0 that the samples come from, the same population (i.e., $\mu_1 = \mu_2$ where μ is the normal population mean, and $o_1 = o_2$) one uses the t score given by

$$t = \frac{X_1 - X_2}{o\,(1/N_1 + 1/N_2)^{1/2}} \quad \text{where} \quad o = \frac{N_1 s_1^2 + N_2 s_2^2}{N_1 + N_2 - 2} \qquad \text{Eqn 1A}$$

The distribution of t is Student's distribution with $u = (N_1 + N_2 - 2)$ degrees of freedom.

In the present analysis, X_1 and X_2 are replaced with K_{virgin} and K_{react}, C_{virgin} and C_{react} and R_{virgin} and R_{react} in run one, for example, for the specified parameters. The non-linear curve fit program calculates standard deviations for the K, C, and R coefficients which are used for standard deviation values, s, in eqn. 1A. N values are the number of non-missing data points for a given, single run, carbon type and parameter combination.

A short BASIC program was written for an APPLE II microcomputer to calculate all t statistics reported.

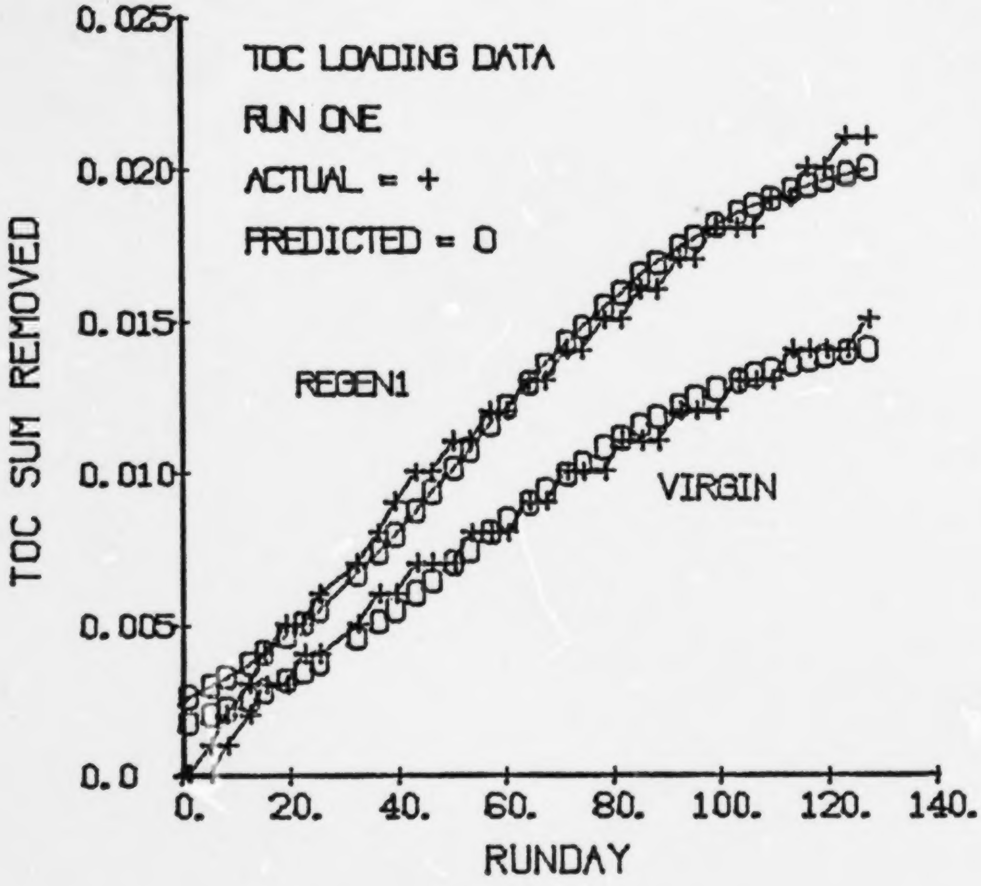

Figure C-1. Run 1 - Statistically Predicted TOC Loading.

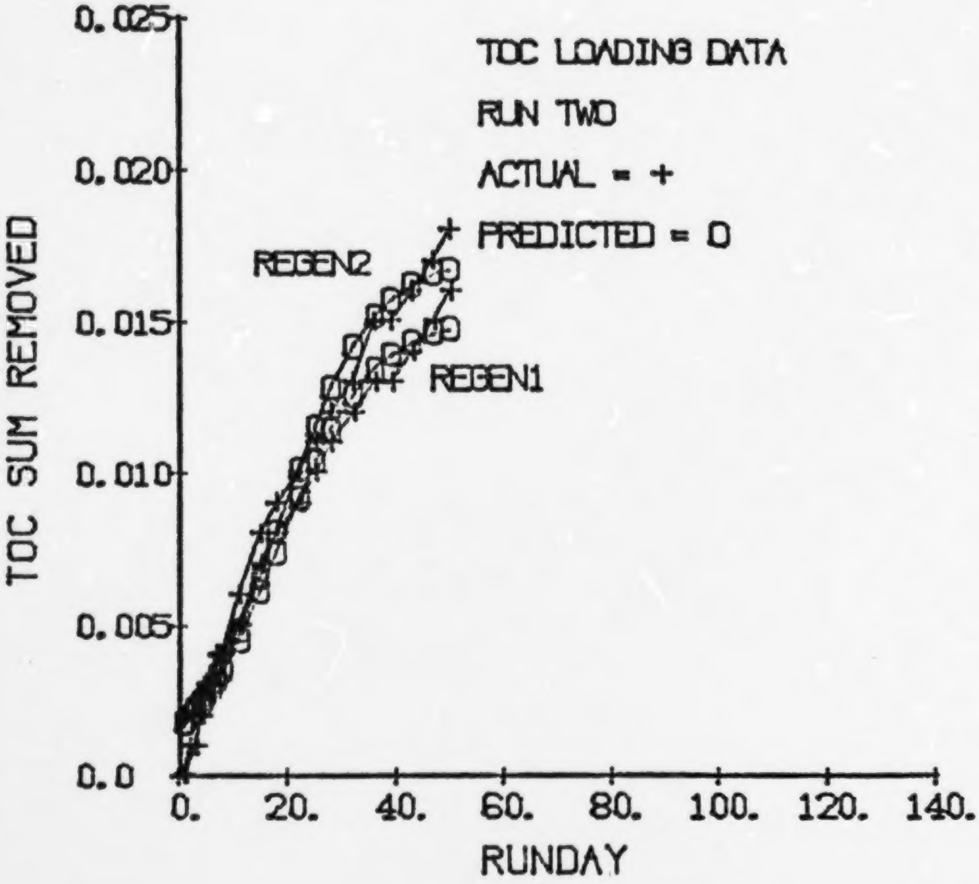

Figure C-2. Run 2 - Statistically Predicted TOC Loading.

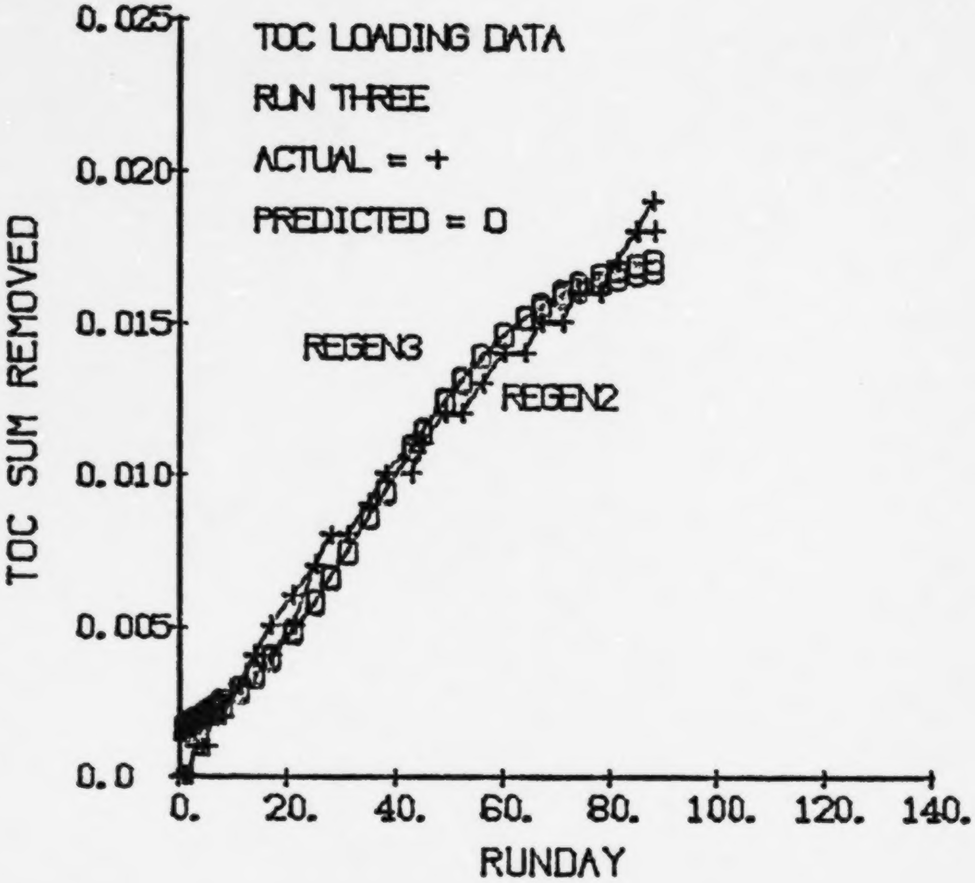

Figure C-3. Run 3 - Statistically Predicted TOC Loading.

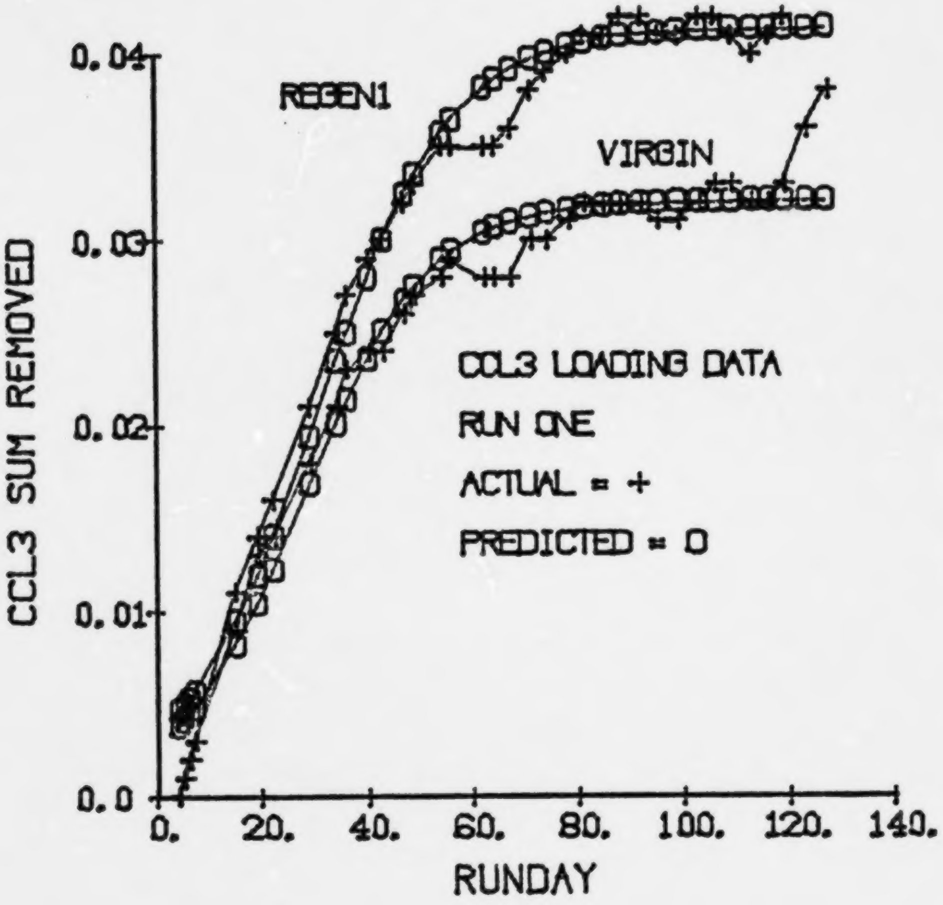

Figure C-4. Run 1 - Statistically Predicted CCL_3 Loading.

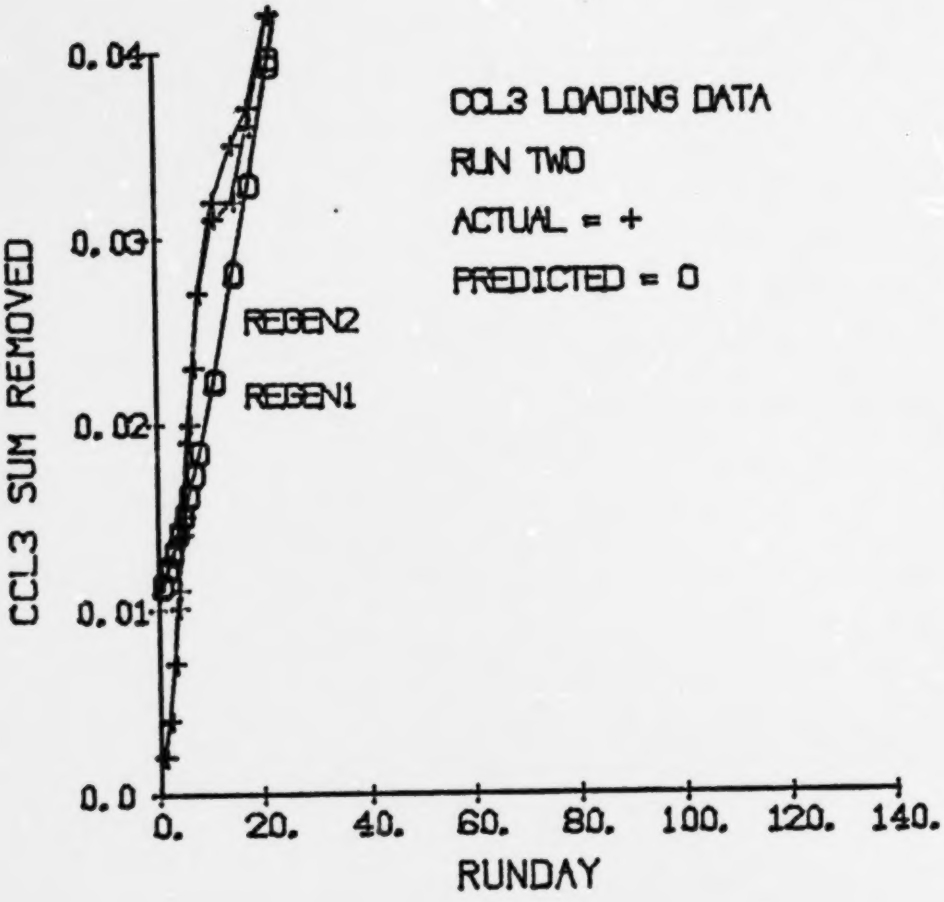

Figure C-5. Run 2 - Statistically Predicted CCL_3 Loading.

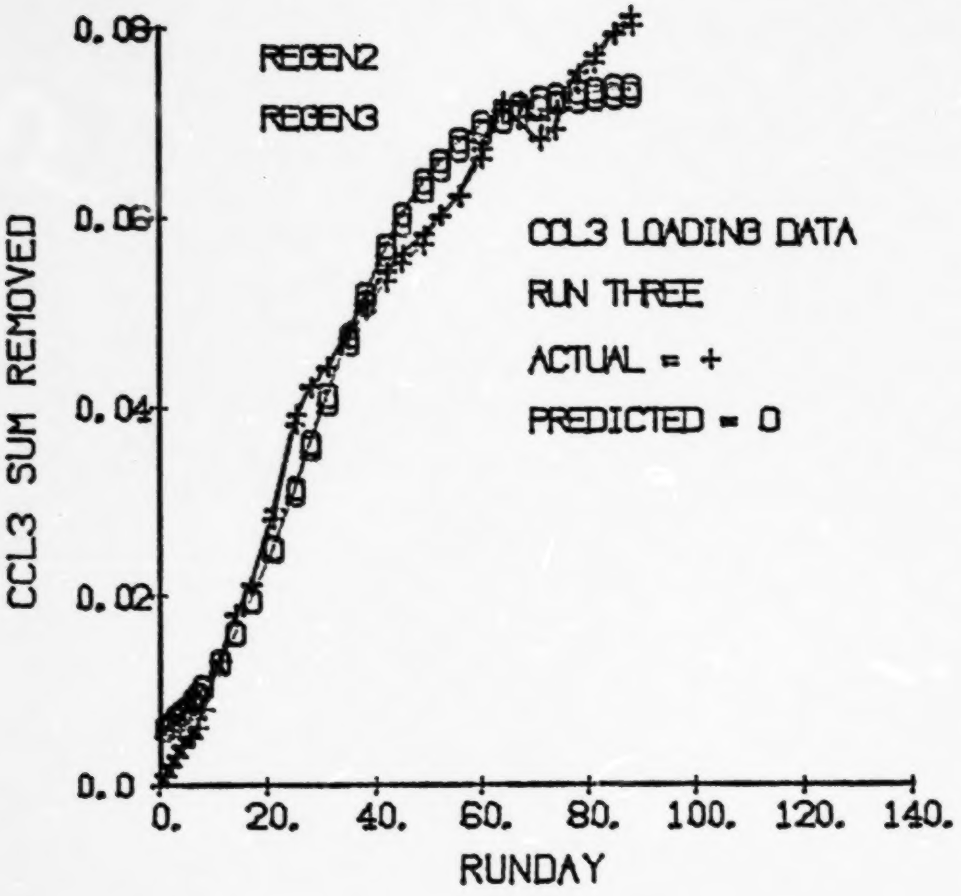

Figure C-6. Run 3 - Statistically Predicted CCL_3 Loading.

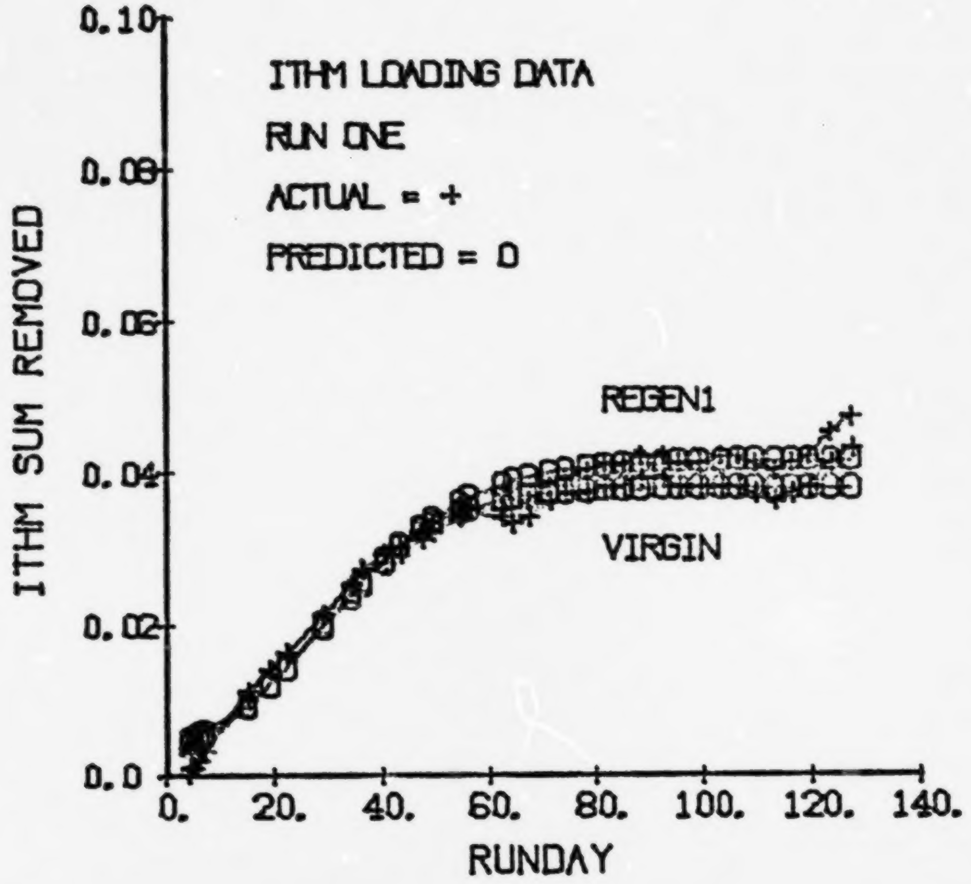

Figure C-7. Run 1 - Statistically Predicted ITHM Loading.

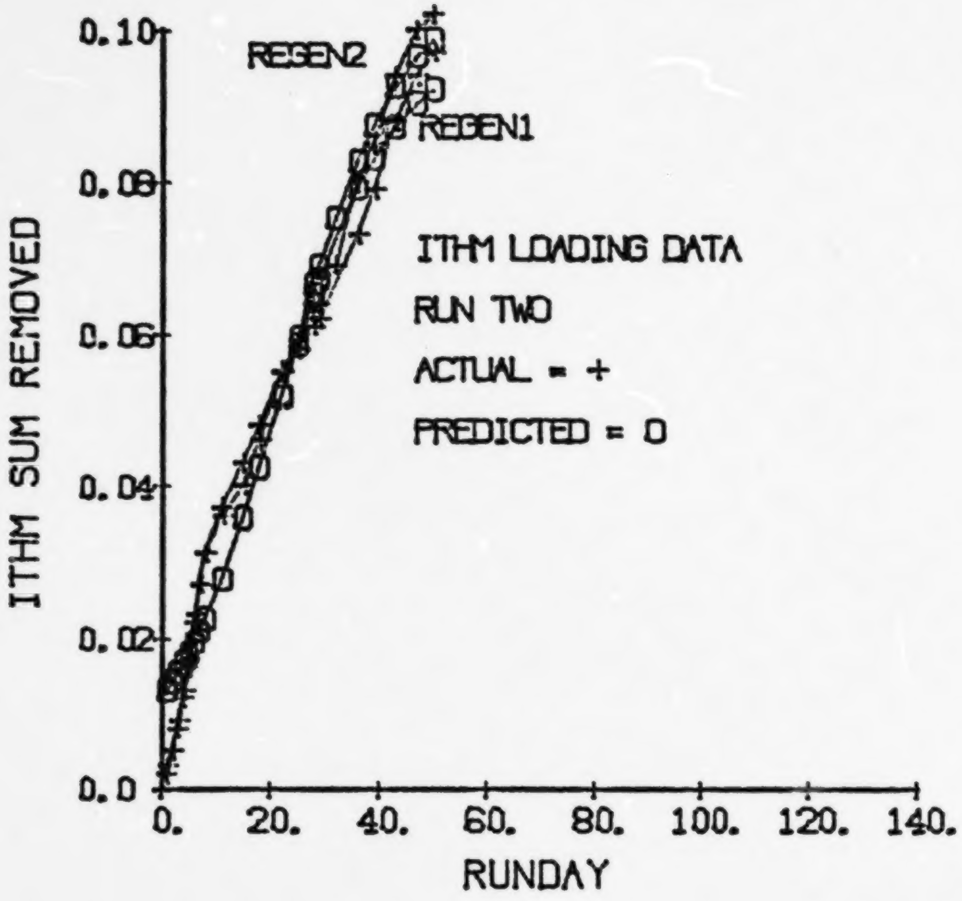

Figure C-8. Run 2 - Statistically Predicted ITHM Loading.

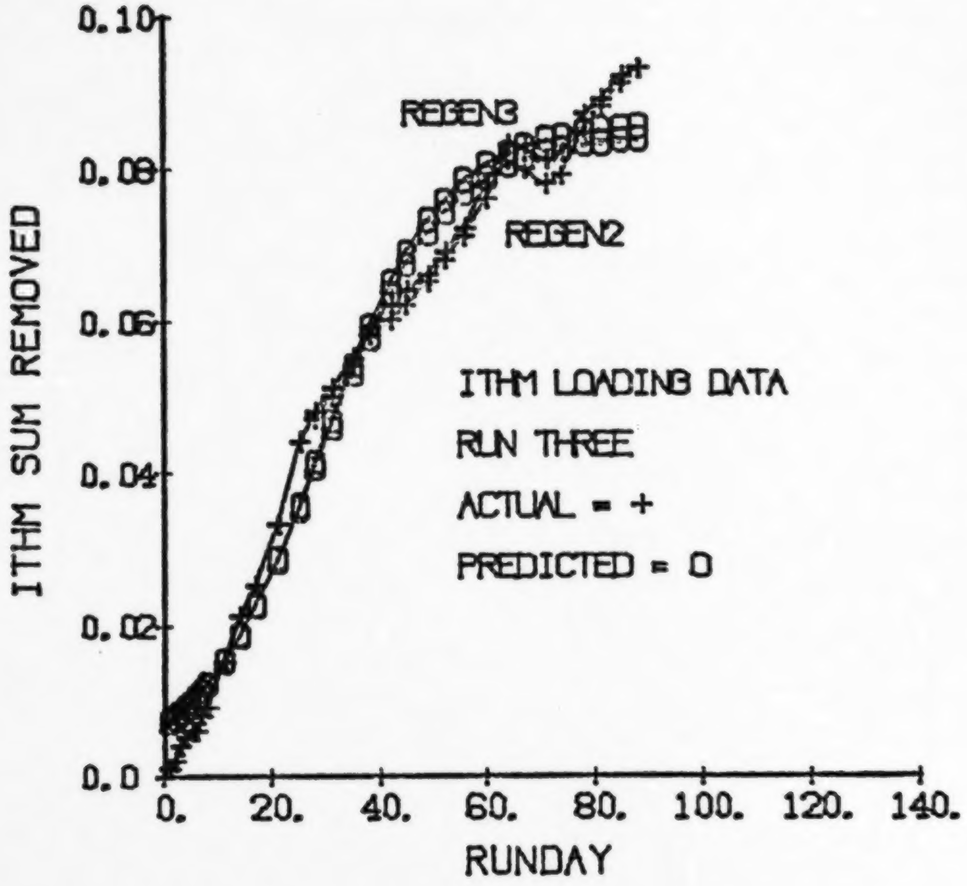

Figure C-9. Run 3 - Statistically Predicted ITHM Loading.

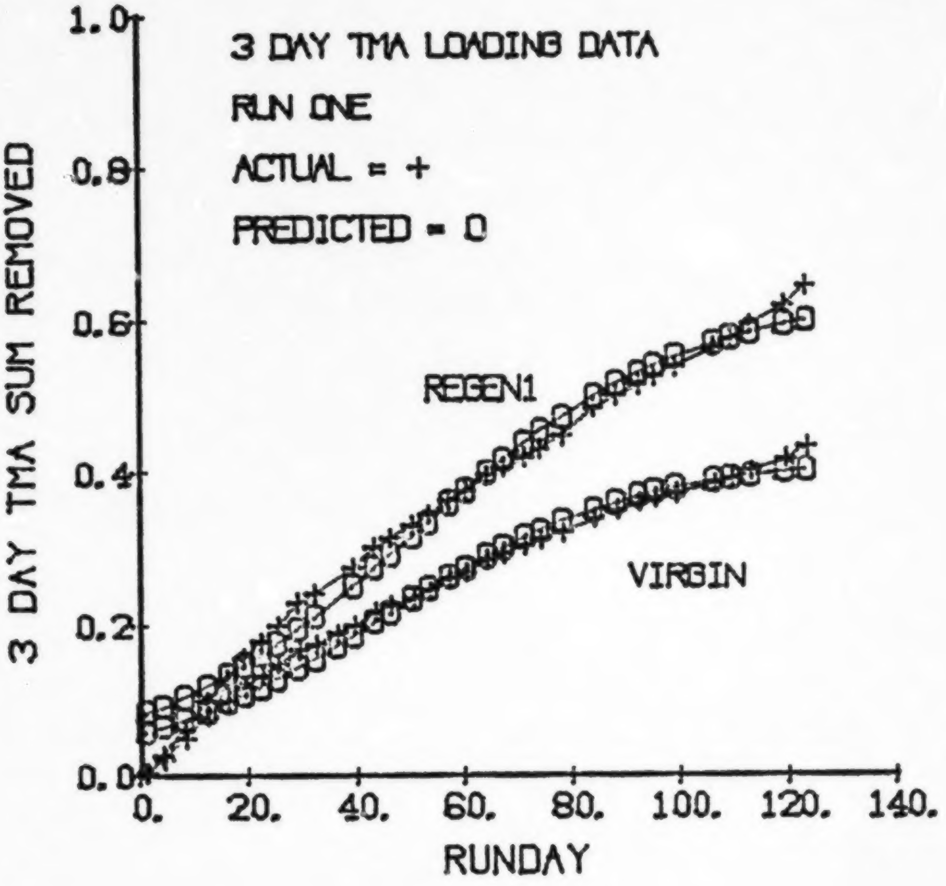

Figure C-10. Run 1 - Statistically Predicted 3-Day TMA Loading.

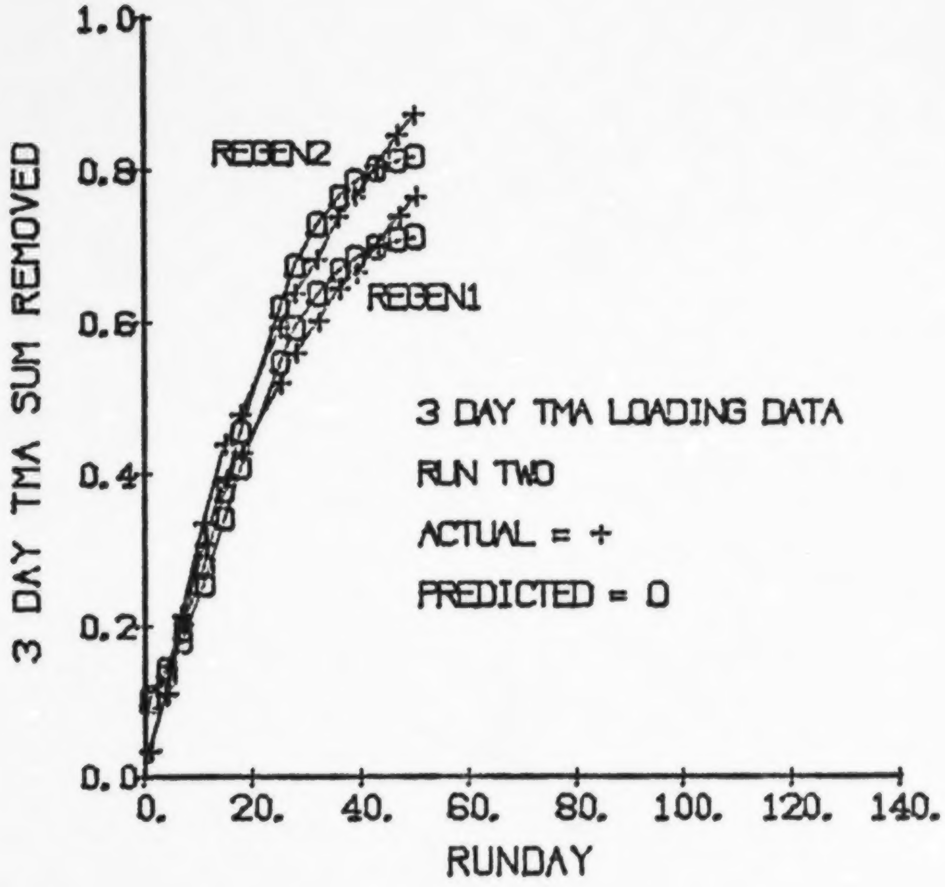

Figure C-11. Run 2 - Statistically Predicted 3-Day TMA Loading.

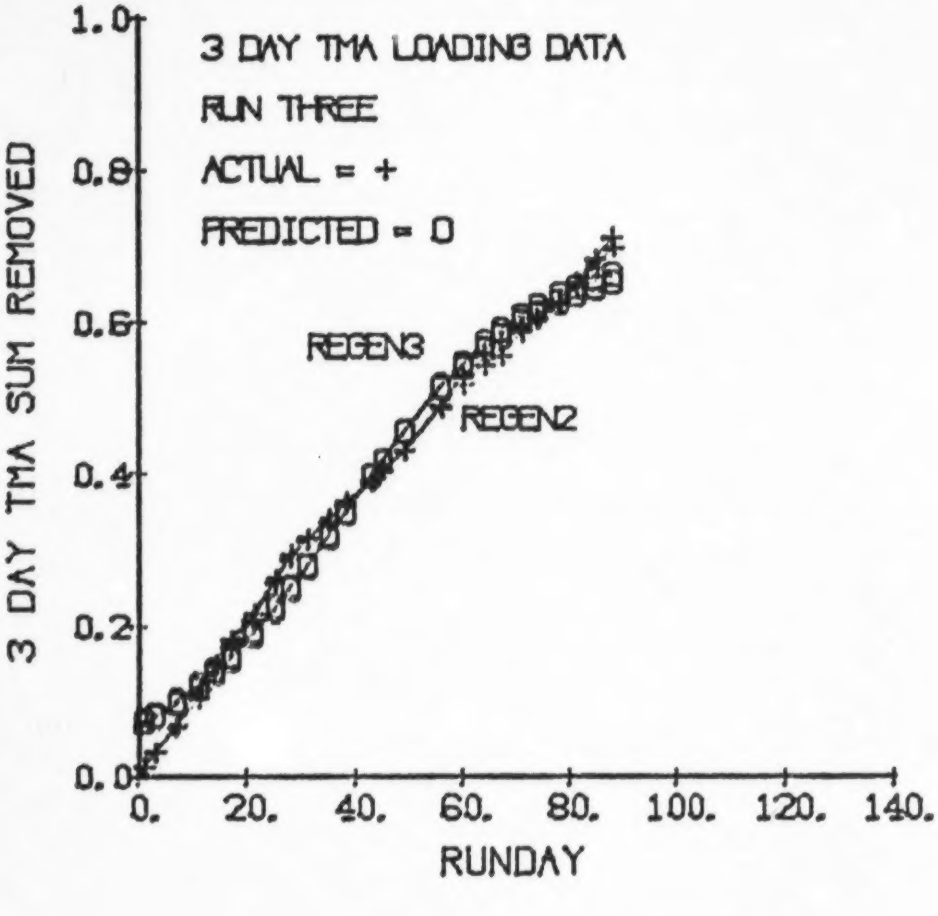

Figure C-12. Run 3- Statistically Predicted 3-Day TMA Loading.

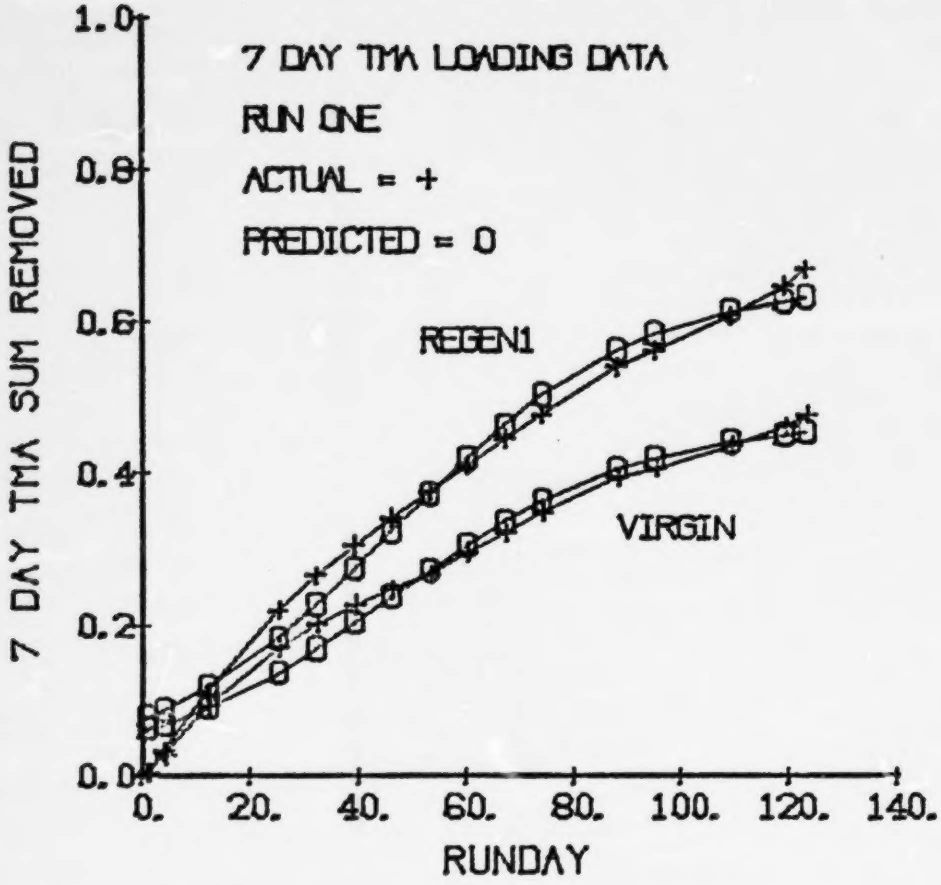

Figure C-13. Run 1 - Statistically Predicted 7-Day TMA Loading.

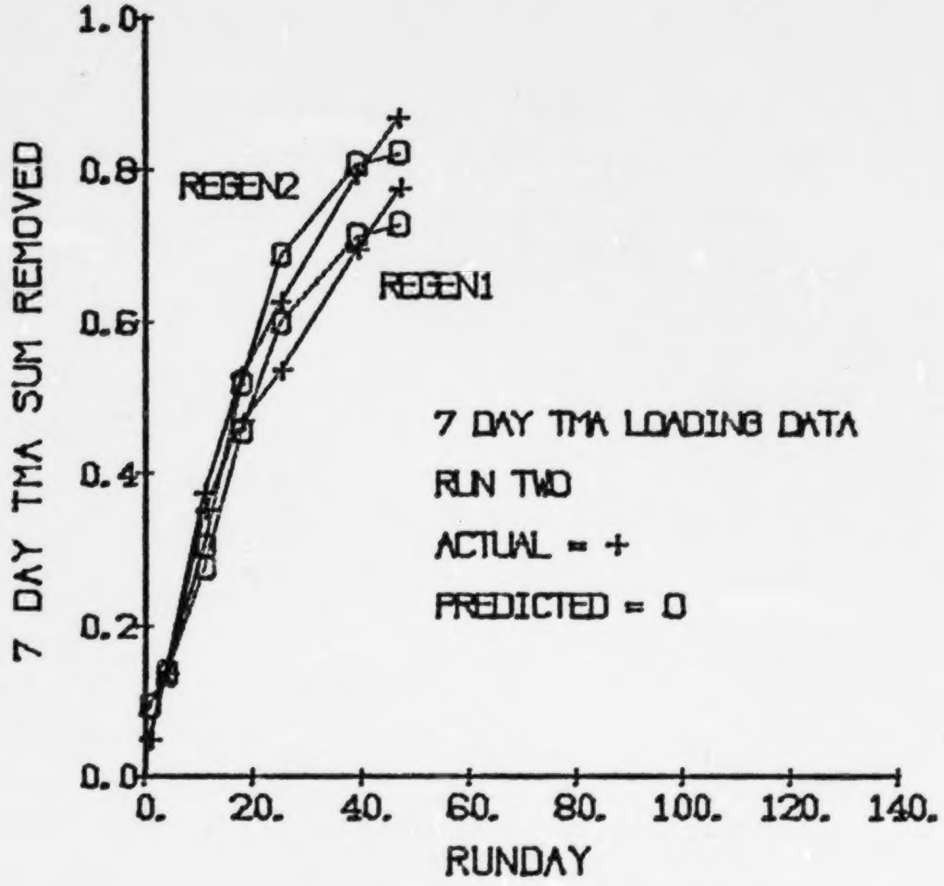

Figure C-14. Run 2 - Statistically Predicted 7-Day TMA Loading.

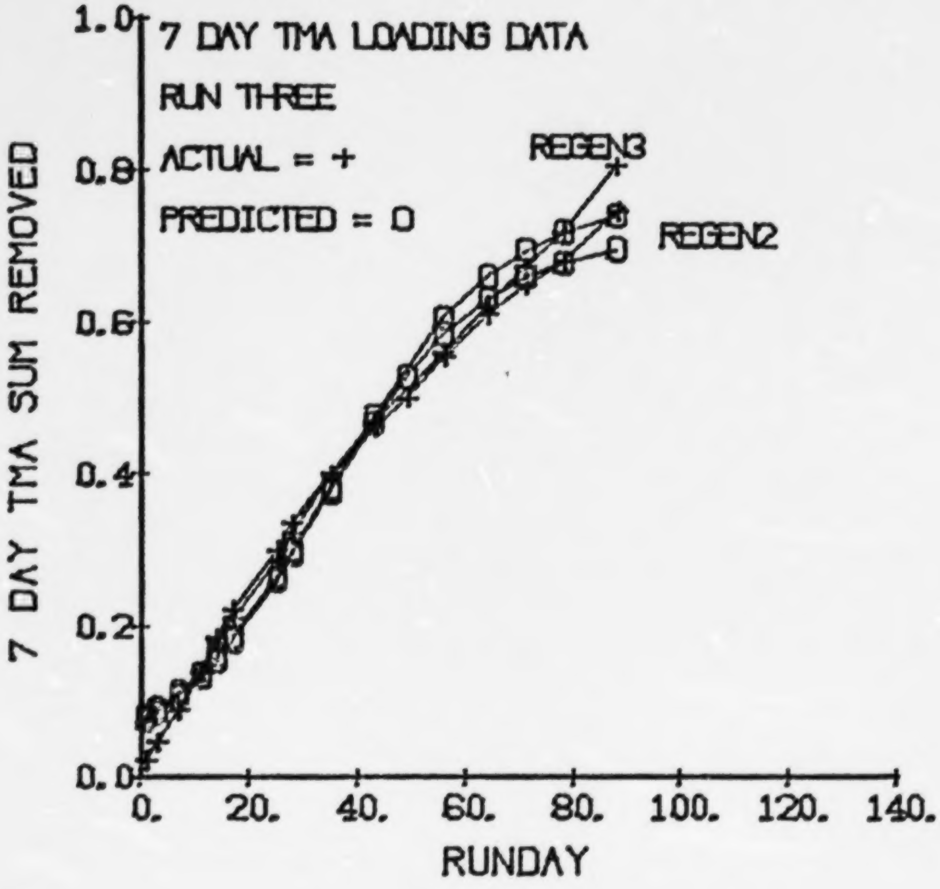

Figure C-15. Run 3 - Statistically Predicted 7-Day TMA Loading.

Gauss-Newton (Bard Algorithm)*

A. Purpose

This program solves for the coefficients in a multivariable, nonlinear regression equation $\hat{Y} = F(X_1, X_2, \ldots, X_K; \hat{A}_1, \hat{A}_2, \ldots, \hat{A}_M)$ utilizing N data points for Y_i and $X_{k,i}$, $i = 1, 2, \ldots, N$; $k = 1, 2, \ldots, K$.

B. Method

The procedure is based on a linearization of the proposed model. A least squares objective function is utilized. The method has proved effective where good starting estimates of the unknown coefficients are available. The algorithm proceeds as follows:

1) The model is linearized by expanding $\hat{Y}_i$ in a Taylor series about current trial values for the coefficients and retaining the linear terms only,

$$\hat{Y}_i = \hat{Y}_i^* + \left[\frac{\partial \hat{Y}_i}{\partial \hat{A}_1}\right]^* \Delta\hat{A}_1 + \left[\frac{\partial \hat{Y}_i}{\partial \hat{A}_2}\right]^* \Delta\hat{A}_2 + \ldots + \left[\frac{\partial \hat{Y}_i}{\partial \hat{A}_M}\right]^* \Delta\hat{A}_M$$

where $\Delta\hat{A}_j = [\hat{A}_j - \hat{A}_j^*]$, $j = 1, 2, \ldots, M$.

The asterisk designates quantities evaluated at the initial trial values.

2) A least squares objective function is formulated,

$$\text{Minimize} \qquad S = \sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2 .$$

3) The linearized model is substituted into the objective function and the "normal equations" formed by setting the partial derivatives of the objective function with respect to each coefficient equal to zero:

$$\frac{\partial S}{\partial \hat{A}_j} = 0, \quad j = 1, 2, \ldots, M .$$

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*The FORTRAN program contained in this section is based on Nonlinear Parameter Estimation and Programming, described on page 237 of "Catalog of Programs for IBM System 360 Models 25 and Above," GC 20-1619-8; program number 360.D-13.6.003. Used by permission of IBM Corp.

The resulting normal equations will be of the form

$$(\underline{A}^t\underline{A})\ \underline{\Delta\hat{A}} = \underline{A}^t(\underline{Y-\hat{Y}^*})$$

where

$$\underline{A} = \begin{bmatrix} \frac{\partial\hat{Y}_1}{\partial\hat{A}_1} & \frac{\partial\hat{Y}_1}{\partial\hat{A}_2} & \cdots & \frac{\partial\hat{Y}_1}{\partial\hat{A}_M} \\ \frac{\partial\hat{Y}_2}{\partial\hat{A}_1} & \frac{\partial\hat{Y}_2}{\partial\hat{A}_2} & & \frac{\partial\hat{Y}_2}{\partial\hat{A}_M} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \frac{\partial\hat{Y}_N}{\partial\hat{A}_1} & \frac{\partial\hat{Y}_N}{\partial\hat{A}_2} & \cdots & \frac{\partial\hat{Y}_N}{\partial\hat{A}_M} \end{bmatrix}^*$$

$$\underline{\Delta\hat{A}} = \begin{bmatrix} (\hat{A}_1 - \hat{A}_1^*) \\ (\hat{A}_2 - \hat{A}_2^*) \\ \cdot \\ \cdot \\ \cdot \\ (\hat{A}_M - \hat{A}_M^*) \end{bmatrix} \qquad (\underline{Y - \hat{Y}^*}) = \begin{bmatrix} (Y_1 - \hat{Y}_1^*) \\ (Y_2 - \hat{Y}_2^*) \\ \cdot \\ \cdot \\ \cdot \\ (Y_N - Y_N^*) \end{bmatrix}$$

$\underline{A}^t$ is the transpose of the $\underline{A}$ matrix. The derivatives in the $\underline{A}$ matrix may be evaluated analytically or numerically.

4) The normal equations are a system of linear algebraic equations and are solved by an appropriate technique for $\underline{\Delta\hat{A}}$. The $\underline{\Delta\hat{A}}$ vector and S will approach zero as convergence is achieved. If convergence is achieved, the final coefficients are calculated from

$$\hat{A}_j = \hat{A}_j^* + \Delta\hat{A}_j, \quad j = 1, 2, \ldots, M .$$

B. 4) Continued

If convergence is not achieved, $\underline{\hat{A}}^*$ is updated by replacing the old values by the new values and the process repeated. A flowsheet illustrating the above procedure is given below.

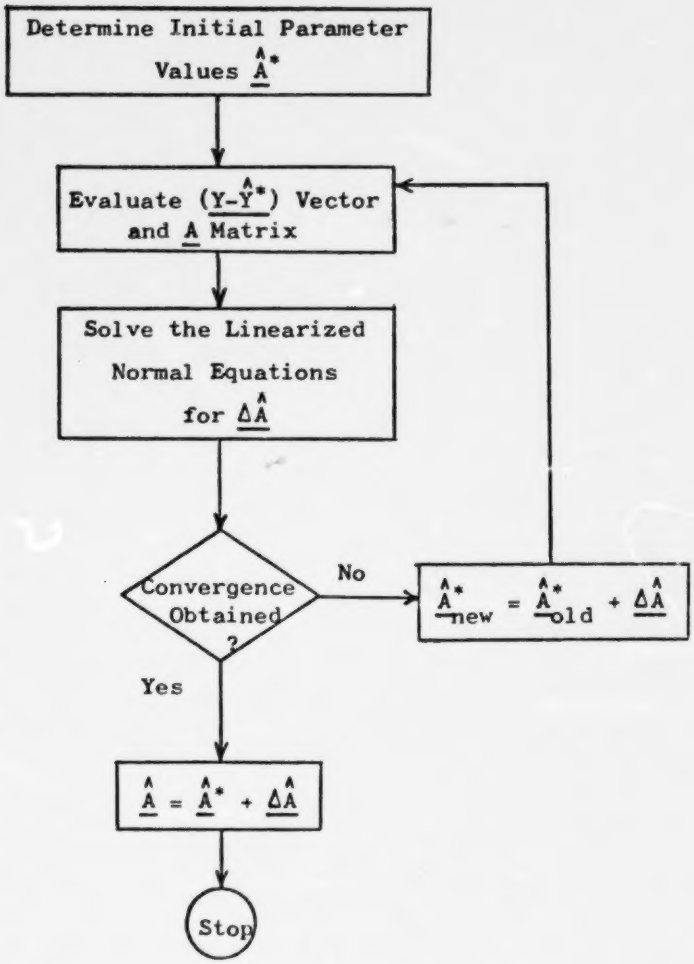
Determine Initial Parameter Values $\underline{\hat{A}}^*$
Evaluate $(\underline{Y-\hat{Y}^*})$ Vector and $\underline{A}$ Matrix
Solve the Linearized Normal Equations for $\underline{\Delta\hat{A}}$
Convergence Obtained ?
No
$\underline{\hat{A}}^*_{new} = \underline{\hat{A}}^*_{old} + \underline{\Delta\hat{A}}$
Yes
$\underline{\hat{A}} = \underline{\hat{A}}^* + \underline{\Delta\hat{A}}$
Stop

Figure C-16. Gauss-Newton (BARD ALGORITHM) Logic Diagram.